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INFLUENCE OF GEOLOGICAL FACTORS ON LONGITUDINAL SEISMIC VELOCITIES[1]

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ABSTRACT

An examination has been made of velocity data obtained from fifty wells located in eight states. There is definite evidence to show that the velocity of shale and sandstone sections increases with the geologic age of the beds. Less reliable evidence points to a similar relationship for limestone velocities.

The velocity of calcareous sandstones and shales is substantially higher than that of a normal sand-shale section.

The effect of depth on the velocity of a given section is investigated. There is a definite increase in velocity with depth in the case of shale and sand sections.

Increase of velocity with age is ascribed to the general increase of the lithification of sediments with age.

INTRODUCTION

The idea that the longitudinal seismic velocity of sediments increases with the age of the sediments has been held rather generally for some time. It was to discover quantitatively what relationship existed that the writers have made an analysis of the velocity measurements available to them in the files of the Geophysical Research Corporation. The data used comprise velocity measurements of good quality taken in fifty wells selected from a total of seventy well velocities available. These wells are located in Mississippi, Louisiana, Texas, New Mexico, Oklahoma, Kansas, Colorado, and Pennsylvania.

[1] Read in preliminary form before the Geophysics Division of the Association at the Dallas meeting, March 24, 1934.

[2] Geophysical Research Corporation. The writers express their thanks to John L. Ferguson, of the Amerada Petroleum Corporation, for his aid in supplying geologic data.

PROCEDURE

The type of data which were analyzed is shown in Figure 1, where velocity-depth curves from three wells are plotted as *AA*, *BB*, and *CC*. These curves have been determined in the usual manner by well shooting. The procedure is to place a charge of dynamite in a hole 20–70 feet deep located about 1,000 feet from a well. A geophone is lowered into the well to some measured depth and this geophone records the time of the first arrival of energy from the exploded charge. The straight-line distance from the shot to the geophone,

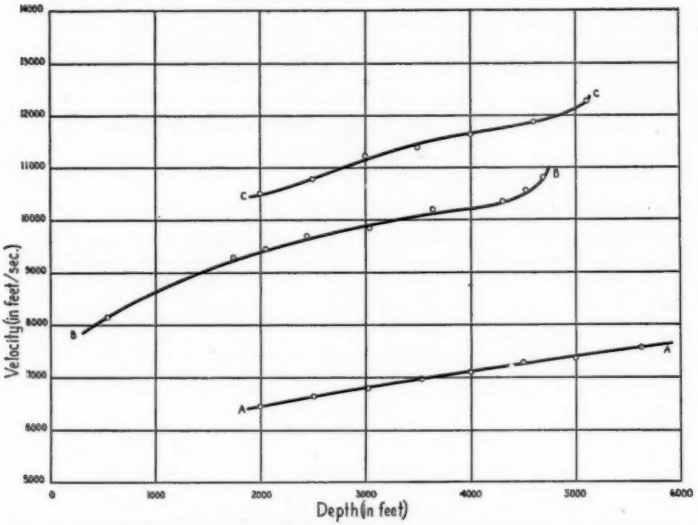

FIG. 1.—Results of velocity determinations in three wells. Average velocity from surface to given depth is plotted against that depth.

divided by this time, gives the average velocity of the section to the depth of the geophone. The velocity so determined is somewhat lower than the average velocity along the actual path of the ray. The actual path of least time is slightly curved and therefore would yield a greater average velocity. The geophone is then lowered to some other depth and another measurement of time is secured and the velocity calculated. It is these velocities plotted against depths of the geophone below the casinghead which are shown in Figure 1.

These curves represent the average velocity of a section from the surface to any depth plotted against that depth. Since the velocity of the first 1,000 feet of material, for example, enters into the velocity

obtained for the first 2,000 feet of section, these curves do not indicate clearly the velocity of the section between 1,000 and 2,000 feet deep. This can be obtained for a vertical path by taking the difference in times of arrival of the energy at the 1,000- and the 2,000-foot depths and dividing it into the difference between the two depths. This velocity is termed the differential velocity of that particular section. On the other hand, the average velocity of the section is measured from the surface to any given depth.

It is the differential velocities which are significant in showing the manner in which velocity varies with depth. The results given in this paper are differential velocities and are determined from actual measurements rather than from a smooth curve drawn through the velocities measured. For the most part, these differential velocities represent the velocity of a section about 1,000 feet thick.

To compare velocity in sections of different geologic age, it is necessary that the sections differ from one another as little as possible in all respects except age. Sections of shale and sand were used chiefly for comparison. A section logged as "calcareous" will give velocities considerably higher than a normal shale and sand section. Curve *CC* (Fig. 1), for example, is a curve of average velocities in Permian and Pennsylvanian beds of calcareous sand and shales. The velocities observed are considerably higher than those in the normal Pennsylvanian section represented by *BB*. This example discloses the need for a careful selection of similar sections so that comparisons of velocities may be significant.

As is shown later, the amount of overburden on a given section influences the velocity of that section. This fact requires that comparisons of velocity in sections of different geologic age be made under the same conditions of overburden.

The data available on limestone velocities is scarce and subject to greater errors than the shale velocities. Velocities of limestone at the surface have been measured by short refraction profiles on the limestone outcrop. These results are open to some question, however, since some alteration in velocity is to be expected due to the weathering of the limestone at the surface.

Measurements of limestone velocities in wells are difficult. Most of the limestone sections available for measurement being less than 400 feet thick and the velocities being high, the error in velocity determinations is considerable. It was not possible to secure a comparison of velocities of limestone sections at exactly the same depth below the surface.

RESULTS

SHALE AND SANDSTONE VELOCITIES

The velocities for shale and sandstone from the surface to a depth of 2,000 feet are given in Table I. The velocity given for each age is an average of velocities obtained in several wells. The individual velocities followed the mean closely.

TABLE I

VELOCITIES IN SHALE AND SANDSTONE TO 2,000 FEET

Age	*Velocity (Ft./Sec.)*
Devonian	13,300
Pennsylvanian	9,500
Permian	8,500
Cretaceous	7,400
Eocene	7,100
Pleistocene-to-Oligocene	6,500

Because of the presence near the surface of the weathered layer of rather indefinite extent, some question may exist as to the accuracy of these results. The effect of this surface layer is canceled out in the determination of differential velocities in sections below the surface. Thus there are no weathering effects in the data in Table II, which shows the differential velocities obtained in shale and sand sections for a section extending from 2,000 to 3,000 feet below the surface, and also for a section from 3,000 to 4,000 feet deep. There is also listed the percentage increase in velocity at the greater depth.

TABLE II

DIFFERENTIAL VELOCITIES IN SHALE AND SANDSTONE

Age	*Velocity from 2,000 to 3,000 Feet (Ft./Sec.)*	*Velocity from 3,000 to 4,000 Feet (Ft./Sec.)*	*Percentage Increase*
Devonian	13,400	13,500	0.7
Pennsylvanian	11,200	11,700	4.5
Permian	10,000	—	—
Cretaceous	9,300	10,700	15.0
Eocene	9,000	10,100	12.2
Pleistocene-to-Oligocene	7,200	8,100	11.2

The data shown in Tables I and II are graphically represented in Figure 2 with some additions at the upper ends of the curves.

Figure 2 can not be said to represent the rate of increase of velocity as a function of depth alone. The velocity of the Pennsylvanian sediments shown in Tables I and II, for example, was secured in part by measurements of sections of the Pennsylvanian of different age in the same wells. Consequently, the increase in velocity with depth could be caused partly by the fact that older Pennsylvanian sediments

were measured as well as by the fact that they were at the greater depths. The relationship between velocity and depth will be signifi-

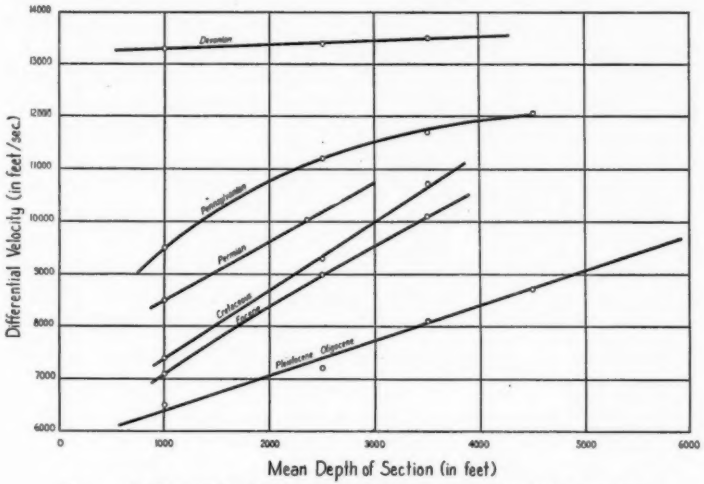

FIG. 2.—Differential velocities plotted against mean depths for sections of different ages.

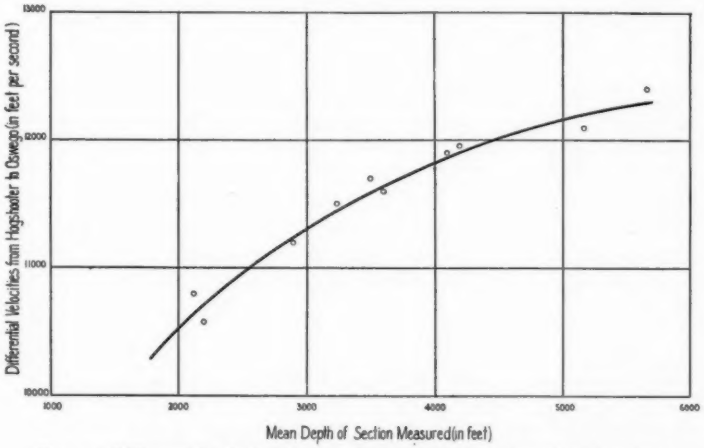

FIG. 3.—Differential velocity in given Pennsylvanian section plotted against mean depth of that section.

cant only when the velocity in a section whose age is kept fixed can be measured while the amount of overburden on that section is varied.

Ideal conditions for determining the velocity-depth function can be approximated by velocity measurements of the section of Pennsylvanian sediments between the Hogshooter and the Oswego. This section is fairly constant in its lithologic character throughout central Oklahoma. The average lime content of the section in the wells where velocity measurements were available was 14 per cent with a maximum variation in any well of 3 per cent from this mean. The average thickness of the section was 750 feet. Figure 3 represents the differential velocity obtained in this section plotted against the mean depth below the surface of the section.

LIMESTONE VELOCITIES

Except for the work of Weatherby, Born, and Harding[3] in the measurement of the longitudinal velocity of Arbuckle limestone, little work has been done on the accurate measurement of surface velocities in limestone. The data available on surface limestone velocities is listed in Table III.

TABLE III

SURFACE LIMESTONE VELOCITIES

Age	*Velocity (Ft./Sec.)*
Cambro-Ordovician (Arbuckle)[3]	17,400
Ordovician (Viola)	16,700
Devonian (Hunton)	14,000
Mississippian (Mayes)	12,500
Pennsylvanian (Belle City)	15,000
Cretaceous (Edwards)	11,000

With the exception of the Pennsylvanian value these velocities follow the age of the limestones in an orderly fashion. The greater velocity of the Pennsylvanian may be due to its having been under a few feet of cover while the rest of these velocities were determined on surface exposures. It should be noted that these velocities may be in rather serious error due to surface weathering and erosion.

TABLE IV

VELOCITIES IN LIMESTONE

Age	*Velocity (Ft./Sec.)*	*Mean Depth of Section Measured (Feet)*
Ordovician	20,000	4,000
Devonian	17,500	4,500
Mississippian	17,000	4,700
Pennsylvanian	15,500	3,000
Permian	15,500	3,900
Cretaceous	13,500	3,300

[3] B. B. Weatherby, W. T. Born, and R. L. Harding, *Bull. Amer. Assoc. Petrol. Geol.*, Vol 18, No. 1 (January, 1934), p. 106.

A list of velocities in limestone at a depth of 3,000–5,000 feet is given in Table IV. Due to the sources of inaccuracy previously mentioned, these velocities may be in error by as much as 1,000 feet per second.

The curve *CC* (Fig. 1) shows a velocity through calcareous Permian sediments to a depth of 2,000 feet of 10,500 feet per second, as against 8,500 feet per second obtained from the average non-calcareous Permian section of this depth. Likewise, the differential velocity on curve *CC* from 2,100 to 3,500 feet is 13,300 feet per second. This is a section of Pennsylvanian beds of 14 per cent limestone and the remainder of the section composed of calcareous sands and shales. A normal section of Pennsylvanian sediments containing 14 per cent limestone and the remainder non-calcareous sand and shale gave a velocity of 11,500 feet per second. A section of 665 feet of these normal sediments plus 735 feet of Pennsylvanian limestone gives the velocity equivalent of the calcareous section.

DISCUSSION

The results obtained show conclusively that the velocity of non-calcareous sections of shale and sandstone increases with the geologic age of the section. That a similar condition holds for velocities in limestone seems to be indicated.

Figure 3 shows the rate of increase of the velocity in a Pennsylvanian section of fixed age with the depth of that section. A comparison of the curve with the Pennsylvanian curve of Figure 2 shows that these two curves agree fairly well. This suggests that the two major causes of variation of velocity in fairly thick sand and shale sections are age and depth. If this is correct, we may consider the group of curves of Figure 2 as being representative of the rate of increase of velocity with depth in shale and sandstone of any given age. It might be expected that the more recent beds, being of lower velocity, would exhibit a greater rate of increase of velocity than the older beds. This appears to be true of the velocities from Cretaceous to Devonian which show some tendency toward approaching the Devonian velocity-depth curve asymptotically. However, the Eocene and more especially the younger sediments show not only a lower rate of increase of velocity with depth but also show a lower percentage increase. A possible explanation for the slower rate of increase of velocity in these younger sediments may be found in the manner of their deposition. In the wells where velocities were measured, these beds were composed mostly of land sediments. They are less tightly cemented than the older sediments which are chiefly marine. It might, therefore,

be expected that such sediments would show a different rate of increase under compaction, since the increase of density tending to decrease the velocity might be greatest in uncemented materials.

The increase of velocity with age appears to be linked with the general increase of the lithification of sediments with age. This appears especially reasonable in view of the high velocities observed in sections of calcareous sand and shales.

The formula for longitudinal velocity (v) in a solid is given by the equation

$$v = \sqrt{\frac{k + 4/3n}{\rho}}$$

where k is the bulk modulus, n the rigidity, and ρ the density of the solid. It is, therefore, apparent that any increase of density of a section with depth would tend to decrease the velocity. Since an increase of velocity with depth is observed, it is apparent that the numerator of the equation must be increasing more rapidly than the denominator. That is, either incompressibility or rigidity or both increase with depth more rapidly than the density. Likewise the effect of lithification must be to increase the elastic constants at a greater rate than the density.

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EFFECT OF MOISTURE UPON VELOCITY OF ELASTIC WAVES IN AMHERST SANDSTONE[1]

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ABSTRACT

Laboratory measurements of the velocity of elastic waves in Amherst sandstone show that the bar velocity is dependent on the moisture content, the velocity decreasing as the moisture content is increased. Bar velocities ranging from 7,640 to 4,415 feet per second were observed. It is shown that the change in velocity is caused primarily by a change in the value of Young's modulus of the material. The suggestion is made that this phenomenon may have some bearing on the question of Gulf Coast reflection surveys.

INTRODUCTION

In the course of a program of work being carried on at the laboratory of the Geophysical Research Corporation to determine the velocity of elastic waves in various materials, it was found that one of the samples used showed variations in velocity from day to day of an amount entirely too great to be accounted for by experimental errors. The determinations were made with the sample in an air-dry condition and it was therefore suspected that the velocity variations observed might be caused by a change in the moisture content of the sample due to varying atmospheric conditions. This supposition led to the work here described.

DESCRIPTION OF SANDSTONE

The sample used was a bar of Amherst sandstone approximately 2 inches square and 4 feet long. This rock is fine-textured sandstone of Triassic age, outcropping in the Connecticut Valley. The sample was one of a number obtained from a local stone cutter who, unfortunately, was unable to specify the exact location from which it was obtained. The density of a dry sample of this material was found to be 1.92. To obtain an idea of the total porosity of the stone, a sample

[1] Read before the Geophysics Division of the Association at the Dallas Meeting, March 23, 1934.

[2] Geophysical Research Corporation. The writers wish to extend their thanks to Miss Margeret C. Cobb and Bruce H. Harlton, both of the Amerada Petroleum Corporation, for their study of the rock section, and also to Parker D. Trask and K. E. Lohman of the United States Geological Survey for their kindness in furnishing the photomicrographs.

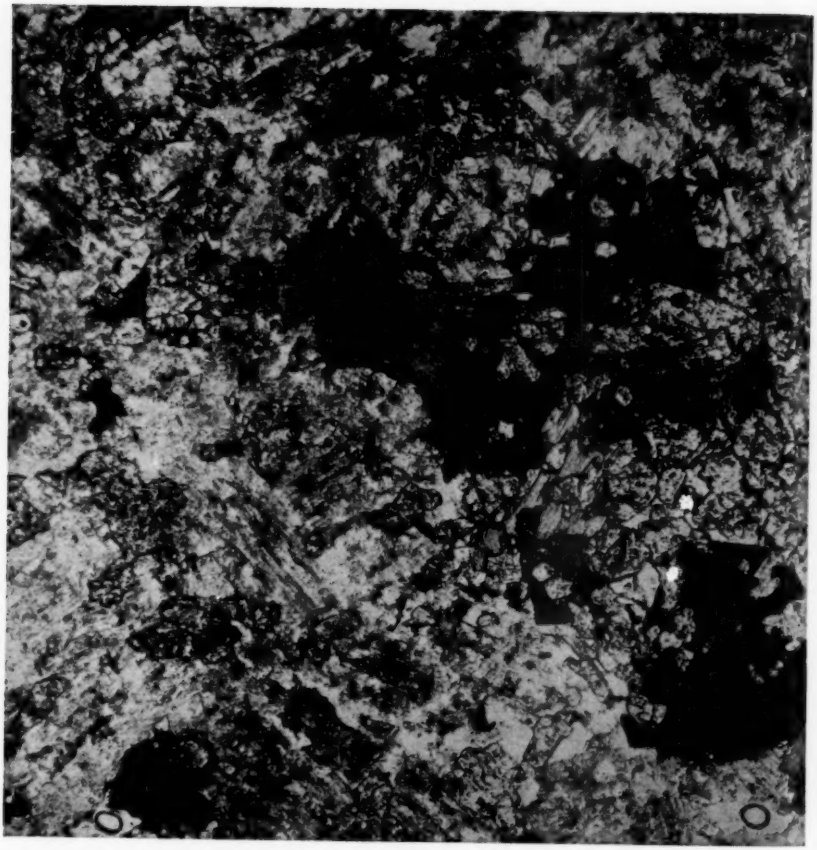

FIG. 1.—Photomicrograph of Amherst sandstone. Ordinary light; magnification 35×.

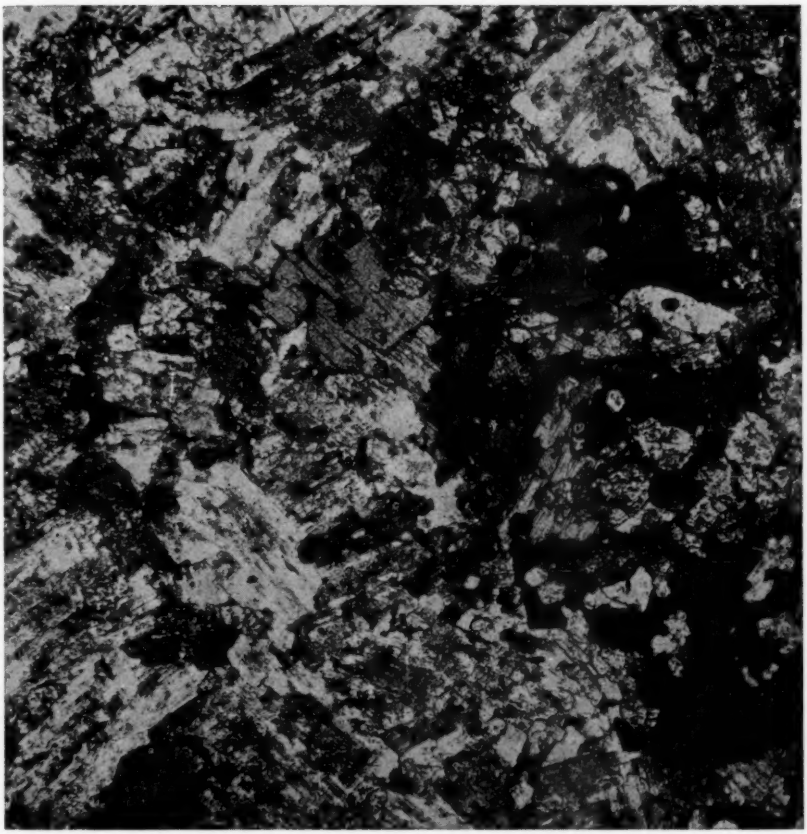

FIG. 2.—Photomicrograph of Amherst sandstone. Polarized light; nicols crossed; magnification 35×.

of measured volume was weighed, evacuated, saturated with water and reweighed. It was found that the sample absorbed 23 per cent of water by volume or 12 per cent by weight.

In order to ascertain the structure of the rock, a section was made for microscopic study. Through the courtesy of Parker D. Trask, of the United States Geological Survey, several photomicrographs of the section were obtained and are here reproduced in Figures 1 and 2. The following brief description of the section is the result of examinations made by Miss Margaret C. Cobb and Bruce H. Harlton, of the Amerada Petroleum Corporation.

The rock is a comparatively pure quartz sandstone. It shows no secondary growth of crystals. The bond is a very fine siliceous iron-bearing silt. Excellent porosity is developed. Feldspar is almost completely absent. Magnetite, hematite, and chloritic alteration products from mica, as well as holite itself, are fairly abundant, and there are the usual heavy residuals.

It is of interest and importance to note that the major constituents of this sandstone are insoluble in water. In order to obtain a rough idea of the amount of water-soluble material present, a 200-gram sample was pulverized and digested with 500 cubic centimeters of distilled water at room temperature for a period of 4 hours. The water was decanted and filtered, the filtrate evaporated to dryness, and the residue weighed. In this way the water-soluble material was estimated to be less than 0.05 per cent by weight.

METHOD AND RESULTS

The method used is a refinement of a method previously[3] described. The apparatus used is shown schematically in Figure 3. The sample bar is held in a horizontal position by a support at its midpoint. Small

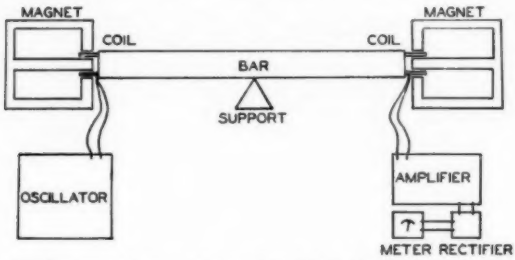

FIG. 3.—Arrangement of apparatus used to determine natural frequency of bar.

[3] B. B. Weatherby, W. T. Born, and R. L. Harding, "Granite and Limestone Determinations in Arbuckle Mountains, Oklahoma," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 18, No. 1 (January, 1934).

coils of wire are attached rigidly at either end, these coils being placed in a radial magnetic field. The coil at one end of the rod is connected to a calibrated variable-frequency oscillator, while that at the other end is connected through an amplifier to a rectifier and galvanometer. Suitable means are provided to measure and to adjust the current supplied by the oscillator to any desired value. The bar may thus be driven at any desired frequency and the amplitude of the motion at the further end of the bar is indicated by the magnitude of the galvanometer deflection. By holding the driving current constant while varying the oscillator frequency, a resonance curve may be drawn by plotting galvanometer deflection against the frequency of the driving current. In this manner the frequency corresponding with the natural frequency of the bar may be easily and accurately obtained.[4] Although the bar is capable of a number of modes of vibration this arrangement of apparatus allows the desired mode, in this case, the fundamental longitudinal vibration, to be easily distinguished.

Having obtained the natural frequency of the bar, the velocity of elastic waves through it may be calculated at once by means of the relationship[5]

$$v = 2fl$$

where v is the velocity
f is the natural frequency
and l is the length of the bar.

The velocity thus calculated is the so-called "bar velocity" which is in general lower than the "bulk velocity" obtained in field measurements. The ratio of these two velocities is a function of Poisson's ratio for the material. In what follows the term velocity is used to denote the measured bar velocity, unless otherwise stated.

To obtain quantitative data showing the effect of moisture upon the velocity of the sandstone, the percentage of water in the rock was varied, and the natural frequency corresponding to each moisture content was determined. The data obtained are shown graphically in Figure 4, in which the observed natural frequencies are plotted against total weight of the bar. The points on the curve were obtained in the order shown by the numeral opposite each. Point 1 was taken with the sample in an air-dry condition, that is, after it had been

[4] In calculating the natural frequency of the bar from the observed data, a correction is made to take into account the effect of the mass of the coils attached to either end. In the present investigation this correction was negligible.

[5] This relationship is strictly true only if the length of the bar is very large as compared with its other dimensions. In the case of short bars a correction must be applied. This correction is negligible for the bar used in this investigation.

lying in air at room temperature for several months. The observed natural frequency was 901 cycles per second and the weight 6,450 grams. The rod was then placed in an oven at 95°C. for a period of 20 hours, and after it was allowed to cool to room temperature, the weight was found to be 6,440.7 grams and the natural frequency 931 cycles per second (Point 2). The weight of the bar after this baking process was taken to be the "dry" weight, that is, the assumption was made that only a negligible amount of water remained after this baking period. The rod was then moistened and placed in a closed tube at room temperature for a period of 36 hours in order to allow the moisture to distribute itself throughout the bar. The weight and natural

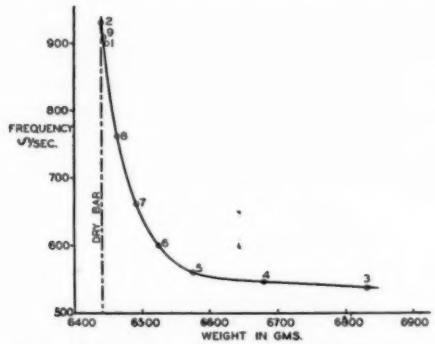

FIG. 4.—Variation in natural frequency of Amherst sandstone bar with weight as water content is changed.

frequency were then determined again, the former being 6,831.3 grams and the latter 538 cycles per second. These values are those corresponding with Point 3 on the curve. The rod was next allowed to dry in air for several hours and then placed in a closed tube for a day to reëstablish moisture equilibrium. Point 4 indicates the weight and natural frequency after this procedure. Subsequent determinations, corresponding to points 5, 6, 7 and 8, were made in similar fashion. To obtain Point 9, the rod was again baked for about 5 hours and the weight and natural frequency determined.

Several features of this curve are of interest. Perhaps the most striking is the extremely rapid reduction of velocity which accompanies the addition of the first increments of moisture and the slower reduction as a greater amount of water is added. A second interesting point is the fact that the curve indicates that the addition and removal of the water caused little, if any, permanent change in the

character of the rock. In other words, the "moisture cycle" appears to be reversible. This is evidenced by the fact that points 1 and 2 fall so nearly on the curve determined by the remaining points. This fact must be taken into consideration in seeking for an explanation of the observed phenomena.

Figure 5 is a graph derived from the observed data. In this figure the calculated velocities in feet per second are plotted against the percentage of water added to the dry bar, the weight of the latter being taken as the base. This curve shows most clearly the very small

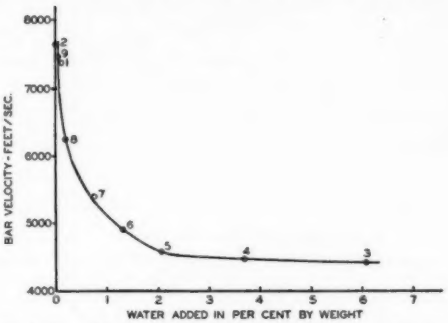

FIG. 5.—Variation of bar velocity of elastic waves in Amherst sandstone as water content is changed.

amount of moisture necessary to cause a great decrease in velocity. The addition of slightly more than 2 per cent of water to the dry bar decreases its velocity from 7,640 feet per second to 4,600 feet per second, which is a reduction of 40 per cent. The addition of 4 per cent more water, however, decreases the velocity to 4,415 feet per second, which is a further reduction of only 2 per cent.

In order to formulate an explanation for the phenomena described, it is first necessary to determine what property of the bar is affected by the moisture. The bar velocity is a function of the value of Young's modulus and the density of the bar, being given by the relationship

$$v = \sqrt{E/\rho}$$

where v is the bar velocity
E is Young's modulus
and ρ is the density of the bar.

A decrease of velocity may therefore be caused by an increase in density, by a decrease in the value of Young's modulus, or by both. The addition of water does, of course, increase the density, but this

increase is far too small to account for the large changes in velocity observed.[6] It might therefore seem safe to conclude that the presence of moisture decreases the value of Young's modulus. It is, however, conceivable that the presence of a small amount of water might exert a loading effect upon the vibrations of the bar and consequently reduce the velocity to a much greater extent than would be anticipated. In order to show that water actually changes the value of Young's modulus by an amount approximately sufficient to account for the observed change in velocity, it was necessary to resort to a static method of measuring the change in Young's modulus. This was done in the following fashion. The bar was supported at either end and loaded at its center point. A fiducial point at the center of the bar was observed with the aid of a micrometer microscope in order that the deflection of the center under various loads could be determined. This deflection, to a first approximation, is given by the relation

$$D = K/E$$

where D is the deflection
E is Young's modulus
and K is a constant involving the distance between the supports and the dimensions of the bar.

The data so obtained were found to be in accord with the supposition that water changes the value of Young's modulus rather

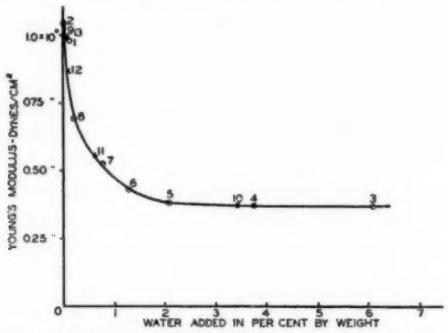

FIG. 6.—Variation in Young's modulus of Amherst sandstone as water content is changed.

[6] The increase in density of the bar produced by the maximum amount of water added was a trifle more than 6 per cent. The maximum decrease in velocity which may be attributed to the change in density is therefore about 3 per cent, whereas changes as great as 42 per cent were observed. In this connection it is of interest to note that the changes in velocity corresponding to that portion of the curve of Figure 5 lying between points 3 and 5 are sufficiently small so that they may be attributed to the change in density.

than the effective density of the bar. This agreement is illustrated by Figure 6. The circled points on the curve are calculated from the observed velocity and measured density of the bar. The points indicated by crosses are those derived from the static measurement. In plotting the latter no effort was made to evaluate accurately the constant K because the cross section of the bar was somewhat irregular. The constant was chosen to make one point fall on the dynamic curve. The others then fell on the curve within the limits of experimental error, which was approximately 2 per cent.

DISCUSSION

The conclusion to be drawn from the work here described is that the observed changes in the velocity of sound in the sample used are primarily due to the observed changes in Young's modulus. In order to formulate an explanation for the phenomena it is therefore necessary to account for the change in Young's modulus as the water content of the sample is varied. Sufficient data are not available at the present time to permit the formulation of a definite explanation of the observed phenomena, but the following discussion is of interest in this connection.

Since the mineral constituents of the rock are highly insoluble in water, it seems safe to conclude that the elastic properties of the individual rock particles themselves are not affected by moisture. The effect may then be localized in the bond holding the particles together. If we picture the rock as made up of particles held together by a bonding material which combines with water as does glue or gelatine, the rock should act somewhat as was observed. A comparatively small amount of a bonding material evenly distributed throughout the sample could, by softening or dissolving, release a large number of bonds and thus cause a large change in the velocity. This explanation fits the observed facts, since the velocity would tend to approach a minimum value determined by the amount and distribution of the bond present. Furthermore, the removal of water would allow the bond to recement the particles and thus restore the rock approximately to its original condition.

An immediate objection to this picture as applied to the sandstone under investigation is that the bond in the sandstone seems to be a siliceous silt which is only slightly soluble. Furthermore the percentage of water-soluble constituents in the bar was found to be extremely small. However, since the absolute amount of bonding material present is minute compared with the total mass of the bar it is not necessary that a large absolute amount of material be dissolved or softened

by the water. The process of softening the bond may not be one of ordinary solution. Some hydrolysis of the silica may occur or the bond may form a colloid in the presence of water. It is hoped that further work may make possible a more definite explanation.

PRACTICAL IMPLICATIONS

In considering the practical application of the results obtained, the question at once arises whether a change in the bar velocity of a sample of this sandstone corresponds to a similar change in the bulk velocity of the material as found in the field. It seems almost certain that it should. From an analytical standpoint the bulk velocity must decrease as the bar velocity decreases, unless there takes place simultaneously a compensating change in the value of Poisson's ratio. Furthermore, as the presence of moisture has been shown to affect one of the elastic constants, namely, Young's modulus, there is reason to suppose that it affects the other elastic constants in a similar fashion. While the results of the work described do not permit a quantitative calculation of the effect of moisture upon the bulk velocity it may reasonably be supposed to be of the same order as that found in the case of the bar velocity.

In connection with the practical application of this and other similar work, B. B. Weatherby has called the attention of the writers to the possibility that some of the "geophysical discontinuities" of the Gulf Coast area which reflect seismic energy in spite of the absence of recognized geological discontinuities, may be due to the presence of a moist strata in an otherwise similar section. The suggestion is an interesting one which will require the accumulation of more data before its validity can be tested. There are undoubtedly many factors operating to produce these discontinuities and it seems very probable that the presence or absence of water may prove to be one of them.

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RECENT DEVELOPMENTS IN GRAVITY PROSPECTING ON GULF COAST[1]

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ABSTRACT

The Gulf Coast salt domes found by gravity methods since the discovery of Sugarland are reviewed up to and including the recent discoveries.

Besides the better known torsion-balance method, the growing use of the pendulum and gravity meter characterize the last 2 years of gravity prospecting.

Regional surveys destined to reveal the general gravity grain of the Gulf Coast in relation to the isolated salt masses are steadily growing and emphasize the importance of gravity surveys in geophysical reconnaissance work.

RECENT DEVELOPMENTS IN GRAVITY PROSPECTING

Although several shallow domes were discovered on the Texas Gulf Coast prior to 1927, the main impetus toward increased gravity prospecting was given by the discovery of the Sugarland dome. Since that time domes were found by the torsion balance in rapid succession: Fannett in 1927, Mykawa, Hankamer and Shepherds Mott in 1928, Manvel and Esperson in 1929, Rabbs Ridge and Citrus Grove in 1930, Spurger, Garwood, Livingston, Tomball, and Cleveland in 1933 and Eureka in 1934. In Louisiana the following domes were found: Darrow in 1927, Roanoke in 1928, Iowa and Cameron Meadows in 1929.

Of these, Fannett is the only shallow dome represented by a torsion-balance maximum. All the others are more or less deep-seated and are represented by gravity minima. Many were not discovered earlier because minima were of secondary interest prior to the discovery of Sugarland. Since then the tables have turned completely. Several gravity maxima have been drilled since 1927, but all were rather weak and represented gravel beds or pseudomaxima which are not of a structural nature, but merely a resultant of forces caused by a number of conflicting salt flights. Others were local maximum closures on the regional high trends which are discussed later. The only known oil field on the Gulf Coast producing from a gravity maximum, excepting the shallow cap-rock domes, is the Louise field

[1] Read before the Geophysics Division of the Association at the Dallas meeting, March 23, 1934. Manuscript received, September, 1934.

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in Wharton County, where a maximum extends due south of the producing high wells, where there is a sharp drop from a rather flat subsurface top to the structure. There is no evidence that the Louise is a salt dome. If so, it must be very deep, since wells have been drilled deeper than 7,000 feet without encountering salt.

Undoubtedly the four greatest discoveries by the torsion balance are Sugarland, Rabbs Ridge, Manvel, and Iowa—greatest at least from the economic standpoint.

Full credit for the discovery of Sugarland is given to the North American Exploration Company crew working for H. C. Cockburn. The area had been shot over by refractions several times without being found until the torsion balance showed indications of a minimum. Further refraction seismograph work confirmed the dome.

The Rabbs Ridge dome was found by crews of the Gulf Production Company. Early torsion-balance work gave vague indications, but detailed work in 1929 and 1930 confirmed the presence of a deep-seated salt dome. The picture is not well defined. Lack of permits for work on the southeast necessitated interpolation of isogams over large distances in order to effect the necessary closures. Averaging of gradients was necessarily used to a great extent where irregularities were caused by surface and near-subsurface depositional variations in the Brazos River bottoms. Stations were made very close together. Calculated sections across the gravity anomaly (Δg section) show definitely that Rabbs Ridge is a deep-seated salt dome rather than a part of a regional trough. In that respect, it was also noted that the axis of Rabbs Ridge was not in the direction of the known regional trends.

The Manvel dome was discovered for The Texas Company by the Torsion Balance Exploration Company. Good interpretation was shown in outlining a dome represented by very little closure and hardly any on one side. The actual producing area is south and southeast of the minimum.

Of the other domes listed, Esperson, discovered for the Union Exploration Company by Christian Iden, and Citrus Grove, a Cockburn discovery, are well marked minima.

Hankamer, Chambers County, a Gulf Production Company discovery, stands out fairly well, although obscured on the west side by the strong influence of the shallow Moss Bluff dome.

Garwood, Colorado County, was discovered by the Torsion Balance Exploration Company for the Coyle-Concord Oil Company. Livingston was discovered by the Sloane Prospecting Company and later confirmed. The Shell Petroleum Company discovered Lakeview, where two wells were drilled showing gas and some structure.

Tomball is a discovery by the Vacuum Oil Company and the

Magnolia Oil Company, confirmed by other torsion-balance work and by pendulum work of the Gulf Production Company before being drilled. The Vacuum-Magnolia is also credited with discovering Iowa, Roanoke, and Cameron Meadows in Louisiana.

In this paper, dealing only with developments, no mention is made of the undeveloped prospects or those more or less definitely condemned. It is possible that several prospects will be proved, as the result of further drilling, particularly those that show structurally high wells. In this respect it is important to bear in mind that some deep-seated geophysical dome prospects may be represented as condemned whereas in reality they lack only deep enough tests.

Certain minima undoubtedly represent inceptive or aborted salt domes which either stopped in early Eocene time or were not uplifted later sufficiently to affect horizons within easy reach of the drill and commercial production. Some of these will be drilled when economic conditions and deep-drilling technique have improved, giving some encouragement for commercial success.

RECENT DEVELOPMENTS IN TECHNIQUE AND INSTRUMENTS

In torsion-balance field work great economies have been effected in operation of the crews. Preference has been shown for the smaller instruments because of their easier portability. The introduction of tungsten torsion wires instead of the platinum-iridium wires formerly used, has done away with a great number of fail stations due to temperature effects. This is particularly true where only five points are used of a three-position automatic registration, and there is no check of the drift of the rest position of the instrument due to temperature variations. Recent investigations have shown that a proper adjustment of the torsion head of a balance is essential to obtain reliable readings. This factor was not given all the consideration due it in the past.

Recently a new type of torsion balance was brought to this country by the American Askania Corporation. The beams, instead of being horizontal, or Z-shaped, are hung at an angle on a double suspension attached at the bottom of the torsion wires. This arrangement saves space and the manufacturers claim that 20 minutes is enough to obtain a rest position for this compact little instrument. One hour a d 40 minutes is sufficient to complete a station, a great saving of time. This instrument is easily portable and easily adjusted. Experiments have been made in this climate to determine its sensitivity to temperature changes where variations are very pronounced. The best test of its behavior was at a known location where several reliable instruments checked each other within the allowable of one

Eötvös unit or less. There is no abnormal deviation from a mean gradient value for the location, measured with standard Z-type Bamberg instruments.

Pendulum apparatuses were first introduced by the Gulf Production Company in 1931. The company had instruments working in East Texas and the upper Gulf Coast to check a network of torsion-balance stations extending from Rains County in northeast Texas to Orange County and farther west. These Askania pendulums were contracted to the Gulf Production Company by Ludger Mintrop. Pendulum stations were placed at intersections of converging torsion-balance traverses several miles apart where possible. As a rule fairly good checks were obtained with not enough error seriously to influence any possible interesting anomalies. Occasionally, however, one pendulum station would be several millidynes off, although converging torsion-balance traverses from other reliable pendulum stations would check within a millidyne or less, all radiating from fixed points toward that hub of divergence. When repeated, the pendulum station would generally check satisfactorily.

Over long distances (80 to 100 miles), a certain gradually increasing divergence between torsion-balance and pendulum results was observed. The torsion balance showed a larger total number of millidynes over that distance than the pendulum. This divergence increases gradually on departing from the base station, but only in the direction of increase of gravity. It is proportional to the anomaly between the first and last station of an 80-mile line. Along strike, differences were small.

After study of all possible causes of this error: (1) normal values of torsion-balance stations, (2) latitude correction, (3) corrections of elevation, and (4) Bouguer correction on the pendulum, it was decided that none of these was consistent enough to cause such differences. It was finally concluded that the cause was to be found in the then prevailing plan of two day stations and one night station per large Bamberg instrument. The night-station gradients with falling temperature were always smaller in proportion to day-station gradients made with rising temperature. Since there were two of these to one night station, the tendency would naturally be to increase the total anomaly in an area of uniform gravity increase. These results were not confirmed in areas worked with small Bamberg instruments, or where two night and two day stations were made.

In 1932, the Gulf Production Company introduced its own pendulum apparatus. These instruments now number 10 on the Gulf Coast: 6 field instruments and 4 base instruments near the field of work or as far as the radio transmitting sets can be heard by the field parties. These instruments use quartz instead of the invar pendulums pre-

viously used. They are sensitive to about 3.10^{-4} except for occasional lapses, when one station will suddenly fail for no apparent reason. The probable error is reduced by two observations with four comparisons with two different base stations. It is then only about 2 or 3.10^{-4}. All direct gravity measuring instruments have the problem of daily and periodical drift and sudden jumps or shifts. Constant comparisons with the base stations are essential daily.

These instruments, if operated to effect a network of stations a mile or two apart, are very valuable for regional gravity prospecting. Larger distances between stations are not advisable because interesting areas may be missed by the larger mesh. It should also be remembered that isolated pendulum stations do not give directional data. Interpolations in contouring are somewhat hazardous except with a close net of reliable stations. The Cleveland dome was found by the pendulum and checked by the torsion balance before the first location was made by the Gulf Production Company.

Gravity meters are based more or less on the basic patent of Kenneth Hartley. They consist of a weight suspended on a delicate spring protected from temperature differences. Variations of the length of the spring due to small differences in gravity are read on a dial controlling a regulating device. The optical system is ingenious and projects two filar images that can be made to overlap and coincide by rotating the dial. There are two or three of these instruments in the field. Their sensitivity is similar to that of the pendulum about 2 or 3.10^{-4} under the best conditions. They can be worked much more rapidly and need no timing device except an ordinary watch to note approximate time for the moon correction. On account of the delicate spring mechanism, the instrument needs great care in handling and must be kept constantly at an even temperature. The clamping device is so constructed as to avoid stresses in the spring while clamping and releasing the weight. Very accurate leveling is of prime importance. These instruments cover a large area in a very short time, but can not always be expected to find domes of very little gravimetric expression, where the total anomaly is about the same as the probable error in reading, or dependent on the additive or neutralizing effect of the probable error in enhancing or wiping out the gravity anomaly.

PROBLEM OF REGIONAL SURVEYS

Since 1927 several of the larger oil companies have been tying in isolated torsion-balance surveys in order to get an idea of the regional grain of the Gulf Coastal country. The regional maxima and minima are all nearly parallel with the coast line, that is, their axes extend northeast and southwest or east and west.

Perhaps the best marked are the parallel maximum and mimimum through Galveston, Brazoria, and Matagorda counties into Calhoun County, Texas. Sections across this system show gravity increases ranging from 10 to 15 millidynes from the minimum to the maximum. In general, there is an increase of gravity out to sea along the coast line.

Salt domes seem to be situated on the flanks of these regional features rather than on the top of the maximum or in the minimum troughs. Little may ever be known as to the meaning of these remarkable gravity features on the Gulf Coast, since these effects are obviously the expression of basement features of great depths beyond reach of the drill. They are unlike anything found in other salt-dome regions, including East Texas, North Louisiana, and Germany.

The effect of these regional gravity maxima and minima is that a number of salt domes, even of the relatively shallow intrusive type, like Danbury and Markham, are not easily distinguished except by deducting a regional gradient. The deeper domes are masked altogether except for a slight bulge in the isogam lines, a slight shortening and lengthening of the gradients respectively against, or following, the regional gravity dip.

A knowledge of the extent and intensity of these regionals over relatively large distances is essential in attempting to isolate a deep gravity anomaly dome from the regional effect. Therefore, local torsion-balance surveys are not of much use without definite knowledge of the regional trend obtained by at least one long traverse into the surrounding territory, except with previous knowledge of general regional conditions in the area under examination.

The torsion balance is ideal for exploration work, because from a distance anomalies can be followed until they are definitely localized. Then they can be checked if so desired by reflection shooting for further geophysical proof, to determine if uplift is present within reach of the drill or if the minimum represents an arrested type salt dome with no uplift in the commercially productive horizons.

As to local gravity elongate closures in the bottom of gravity minimum trends (a good many of which have been drilled, even in recent years), most competent geophysicists will condemn them if they are familiar with regional conditions. Such minimum trends, of course, should not be confused with elongate lines or groups of salt domes at various stages of evolution, such as Lost Lake, Moss Bluff, and Hankamer. Prospects in or near the bottom of regional trends gain in value, if at least on one side a good closure is obtained along the axis of the trend. Discrimination is, therefore, necessary and should be the basis on which the competent geophysicist bases his conclusions.

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PREDICTION OF OVERHANG AT BARBERS HILL, CHAMBERS COUNTY, TEXAS: A STUDY IN QUANTITATIVE CALCULATIONS FROM TORSION-BALANCE DATA[1]

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ABSTRACT

A study of the possibility of prediction of the overhang at Barbers Hill was based on quantitative calculations from a diametral torsion-balance profile across the dome and the drilling data in regard to the top of the cap and salt. A series of three alternative positions of the flank of the salt on the left and four on the right were assumed. All combinations of the assumed left and right alternative positions of the edge of the salt were tested. Several variations of the assumed density relations were tested. Several variations of the regional gradient were tested. The gradient profiles which would be produced by the respective assumed forms of the dome were calculated by the writer's graphical method. For the calculated gradient profiles which had the closer fit to the observed gradient profile, the mean-square difference between the calculated and observed profiles was used as the test of the relative closeness of fit. The form of the dome which had considerable overhang on the right and slight overhang on the left consistently had the least mean square. The conclusion therefore is that the overhang at Barbers Hill could be predicted in advance of drilling solely on the basis of torsion-balance data and of whatever data in regard to the cap and salt might be available from drilling.

PURPOSE OF STUDY

This study was made to see whether or not the presence of the overhang at such a dome as Barbers Hill could be determined by calculation from the data of a torsion-balance survey, in advance of determination of the overhang by the drill. The study was based on the assumptions that the form of the top of the cap and the depth to the top of the salt table were known but that there were no drilling data available to show whether or not overhang actually was present. Calculations were then made from the results of the torsion-balance data to see whether or not the presence or absence of overhang could be determined with good, fair, or poor probability of accuracy.

[1] Read before the Geophysics Division of the Association at the Dallas meeting, March 23, 1934. Manuscript received, November 12, 1934. Original data released through the favor of Sidney A. Judson and the permission of the Rio Bravo Oil Company, Sun Oil Company, and Texas Gulf Producing Company.

[2] Humble Oil and Refining Company.

DATA

The data used in the calculations were:

A. Three closely adjacent diametral lines of torsion-balance stations (Fig. 1).

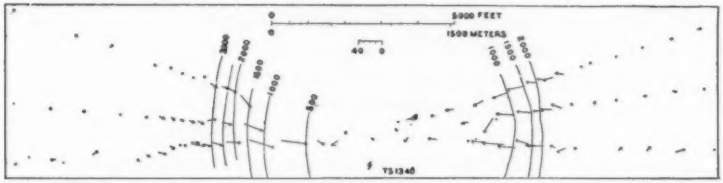

FIG. 1.—Map showing the gradient arrows of the torsion-balance surveys, and the structure contours on top of the cap, from well data, Barbers Hill salt dome.

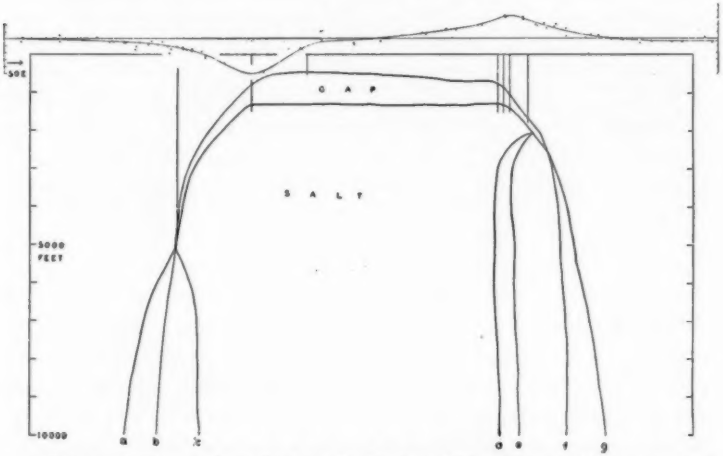

FIG. 2.—Section and gradient profile, Barbers Hill salt dome. Above: gradient profile. Below: structure section showing the known data of the cap and the assumed positions (*a* to *g*) of the flank of the salt core.

The torsion-balance lines were part of a survey by the Torsion Balance Exploration Company for the Humphreys Corporation several years ago and were obtained through the courtesy of Sidney A. Judson of the Texas Gulf Producing Company.

The stations presumably are good normal stations, as the survey was made by the Torsion Balance Exploration Company. For quantitative calculations of this type, care beyond that used normally in the preparation of stations and in the taking of the stations should

be used. But it is not known whether precautions beyond that company's usual good care were used on this survey.

The stations were not placed most advantageously for the purposes of the calculations. It would have been strongly advantageous for this study, if the torsion-balance lines had been extended much farther out from the edge of the dome. Preferably also the stations of two of the lines should have been all on the same line; and the stations of the third line on the ends of that line.

B. The known drilling data in regard to the top of the cap and the top of the salt table. A host of wells have been drilled through the edge of the cap, but over the top of the dome wells are rather sparsely scattered.

C. Past experiences in regard to the probable specific gravities of the cap, salt, and sediments.[3]

METHODS OF CALCULATION

The writer's graphical method of calculating was used.[4]

A chart was constructed specially for use on this diameter of the Barbers Hill dome. These charts are composed of assumed prisms at right angles to the vertical plane of the section. The length of the chart prisms was chosen to fit the northwest-southeast conformation of the cap through the central half of the dome. Corrections were then calculated to make the chart fit the northwest-southeast conformation of the cap in the outer quarters of the northeast-southwest cross section. This chart was used for the cap and salt above a depth of 4,000 feet. A similar chart with slightly different specifications was used to calculate the effects from 4,000 feet down to 12,000 feet. The effect of the salt below 12,000 feet was neglected.

The observed gradient profile had first to be smoothed. Seriously aberrant values were discarded. The smoothing of the others was studied by two methods:

A. By replacing the dot for each observed gradient value by a dot at the center of gravity of the triangle composed of the dot and the adjacent dot on each side, and

B. By the formula:

$$C' = \frac{a + 2b + 3c + 2d + e}{9}.$$

[3] D. C. Barton, "Belle Isle Torsion-Balance Survey, St. Mary Parish, Louisiana," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 15, No. 11 (November, 1931), pp. 1341–42.

[4] ———, "Calculations in the Interpretation of Observations with the Eötvös Torsion Balance," *Geophysical Prospecting, 1929* (Amer. Inst. Min. Met. Eng., 1930), pp. 416–80.

The effect of the cap rock was then calculated. These calculations would have been simple, if the actual form and density of the cap rock had been known. But as a matter of fact, the form of the cap-rock mass along the southwest-northeast diameter is known only approximately, and it is necessary to go through the whole tedious series of trial and error calculations to determine the most probable gradient profile of the cap-rock effect. The observed gradient profile is predominantly the effect of the cap rock. The form of the cap rock was altered within the limits which were imposed by the drilling data; and the gradient profile for each form was calculated. The calculated gradient profile which most nearly fitted the observed gradient profile was assumed to be the actual effect of the cap-rock mass.

Detailed calculations of the salt effect were then made. It was assumed that the edge of the salt core might have any of the forms, *a*, *b* *c*, *d*, *e*, *f*, *g*, of Figure 2. The form might take that of any combination of (*a*, *b*, *c*) with (*d*, *e*, *f*, *g*).

Seventy-eight calculation points, 200 feet apart, were taken, covering the whole length of the torsion-balance profile. The gradient effect of the cap and the salt was calculated for every fifth station. The values for the intermediate stations were interpolated. The difference between the calculated value at each station and the corresponding value of the smoothed observed curve was then recorded. The respective differences were then squared, the squares were added, and the mean square found.

The mean square is taken to be the measure of probability of the particular set of assumptions used in the respective calculations. The less the mean square, the more probable is that set of assumptions. The set of assumptions which has the least mean square is assumed to be the most probable.

Three unknowns have to be evaluated by the trial and error calculation of the least mean square: deviation of the calculated from the smoothed, observed gradient profile:

A. The form of the salt and cap;

B. The relative density of the salt and cap in reference to the sediments; and

C. The regional gradient.

Any one set of assumptions for a given calculation comprises:

A. One of the forms (*a*—*e*), (*a*—*f*), et cetera.

B. A net of assumptions regarding the density of the cap, the density of the salt, the respective density of the sediments at various depths.

C. Some assumption in regard to the regional gradient.

A long series of combinations of these geologically probable assumptions are possible and have to be calculated directly or indirectly.

For many such sets of assumptions, it was unnecessary to carry the calculations through to the point of finding the mean square. If the unsquared differences are plainly large, the mean square necessarily is large. The calculation of any set of assumptions was dropped as soon as it was very evident that the unsquared differences were large.

The work of the construction of the charts and of the calculation was done by the writer's then assistant, Maude Hickey.

Approximately 1 month was spent in calculation in connection with the effect of the cap rock and approximately 3 months on the effect of the salt. The methods evolved considerably during the calculations. Much of the time was spent in refinement of the technique and in recalculating calculations which had been done earlier by less refined technique. It is probable that a similar calculation of a diametral profile could be made by an experienced calculator in 2 months, although if difficulties came up, a slightly longer time might be required. The time required for satisfactory results would vary inversely with the amount of geologic information that would limit the range of variations in our fundamental assumptions.

RESULTS

The calculations indicate that the overhang at Barbers Hill can be detected by calculations based on torsion-balance data, for the results of the calculations indicate that the series of assumed forms rank in the following order of decreasing probability.

		Relative Rating
cd	Maximum overhang	1.00
ce	Overhang both sides but on right not so much as in preceding	0.80
cf	Overhang left; no overhang right	0.44
be	Overhang right; no overhang left	0.43
bf	No overhang	0.22

Preliminary calculations showed clearly that all forms including *a* or *g* would produce calculated gradient profiles which fit the smoothed gradient profile very poorly. Those forms were dropped from the further calculations.

A summary of the results of the calculations for the forms (*b*,*c*) and (*d*, *e*, *f*) are shown in Table I. Many trials which were started are not reported on that sheet, for trials of any set of assumptions were stopped as soon as the unsquared differences were seen to be

TABLE I

MEAN SQUARES OF DEVIATION

			ad	ae	af	ag	bd	be	bf	cd	ce	cf	bg	cg
Density Assumption A														
Varying Regional Gradient		Mean						3.50	3.87	3.00	2.80	3.57		
I-*A*	4 N.E. Stations Omitted	Median						2.03	2.73	1.50	1.44	2.03		
		Sum						5.33	6.60	4.50	4.24	5.60		
II-*B*	All Stations		LARGE	LARGE	LARGE	LARGE	not calculated	3.46	3.69	2.85	2.80	3.40	LARGE	
								2.18	2.40	1.38	1.50	1.94		
								5.64	6.09	4.23	4.30	5.34		
III-*C*	15 Middle and 4 N.E. Stations Omitted							2.39	2.71	1.65	1.63	2.24	LARGE	
								1.92	1.90	1.21	1.17	1.59		
								4.31	4.61	2.86	2.80	3.83		
IV-*D*	15 Middle and 4 N.E. Weight 1 All Others Weight 2							2.99	3.26	2.42	2.29	2.89		
								2.13	2.25	1.30	1.44	1.69		
								5.12	5.51	3.72	3.73	4.58		
No Regional Gradient														
V-*A*				ditto				4.16	5.89	3.53	4.03	6.49		
								3.15	4.85	2.17	3.24	5.53		
								7.31	10.74	5.70	7.27	12.02		
VI-*B*				ditto				4.30	5.72	3.94	4.23	6.31	LARGE	
								3.43	4.42	2.57	3.50	5.29		
								7.83	10.14	6.51	7.73	11.60		
VII-*C*				ditto				3.37	4.78	2.61	2.99	4.86	LARGE	
								2.13	3.69	1.69	2.70	4.81		
								5.50	8.47	4.30	5.69	9.67		
VIII-*D*				ditto				3.90	5.31	3.36	3.69	5.68		
								2.69	4.01	2.02	3.24	5.29		
								6.59	9.31	5.38	6.93	10.97		
Density Assumption B									8.10					
IX-*A*				ditto					6.90					
									15.00					
X-*B*				ditto					7.80					
									6.26					
									14.06					
XI-*C*				ditto					7.60					
									6.16					
									13.76					
XII-*D*									7.71					
									6.15					
									13.86					
Density Assumption C									>20					ditto
Density Assumption D—No Regional														
XIII-*A*									4.14		4.49			
									3.24		1.63			
									7.38		6.12			
XIV-*B*									5.66		5.09			
									3.43		1.76			
									9.09		6.85			
XV-*C*									5.41		3.52			
									2.50		1.17			
									7.91		4.69			
XVI-*D*									5.00		4.41			
									3.24		1.44			
									8.24		5.85			
Regional Gradient >1 <1.5*E*														
XVII-*A*									4.2		3.8			
									1.6		1.1			
									5.8		4.9			
XVIII-*B*									4.2		4.0			
									1.8		1.6			
									6.0		5.6			

bd = very close to *be* — ALL MEAN SQUARES

TABLE I (*Continued*)

MEAN SQUARES OF DEVIATION

First	*Second*	*Third*	*Fourth*	*Fifth*	*Sixth*	*Seventh and Poorer*	
ce	*cd*	(*bd*, *be*, *cf*)		*bf*	(All a's / All g's)		Cap 2.59–2.61 Salt 2.20–2.21
ce	*cd*	ditto		*bf*			
ce	*cd*	ditto		*bf*			
ce	*cd*	(*cf*, *be*, *bd*)		*bf*			Sediments 2.12 to 2.37 at 12,000 feet
cd	*ce*	ditto		*bf*		ditto	
cd	*ce*	ditto		*bf*			
ce	*cd*	*cf*	*be*	*bf*			Regional Gradient $>0, <1.5\,E$
ce	*cd*	*cf*	and	*bf*		ditto	
ce	*cd*	*cf*	*bd*	*bf*			
ce	*cd*	*cf*	*be*	*bf*			
ce	*cd*	*cf*	and	*bf*		ditto	
ce	*cd*	*cf*	*bd*	*bf*			
cd	*ce*	(*be*, *bd*)		*bf*	*cf*		
cd	*be*	(*ce*, *bd*)		*bf*	*cf*	ditto	
cd	*ce*	(*be*, *bd*)		*bf*	*cf*		No Regional Gradient
cd	*ce*	(*be*, *bd*)		*bf*	*cf*		
cd	*be*	(*ce*, *bd*)		*bf*	*cf*	ditto	
cd	*ce*	(*be*, *bd*)		*bf*	*cf*		
cd	*ce*	(*be*, *bd*)		*bf*	*cf*		
cd	*be*	(*ce*, *bd*)		*bf*	*cf*	ditto	
cd	*ce*	(*be*, *bd*)		*bf*	*cf*		
cd	*be*	(*ce*, *bd*)		*bf*	*cf*	ditto	
							Cap 2.60–2.63 Salt 2.21 Sediments 2.13 to 2.38 at 12,000 feet
							ditto
							Cap 2.70–2.74 2.66–2.70 Salt 2.21 also 2.21 Sediments 2.15–2.39 2.15–2.39
							Cap 2.57 Salt 221 Sediments 2.12 to 2.36 at 12,000 feet
							XIII–XVIII are based on cruder calculations.

LARGE

running consistently large. The table gives merely a synopsis of the more important mean squares.

The mean squares are given in 3 forms: the mean, the median, and the sum of the mean and median. The median which is used actually is the mean of the median 4 or 5 squared differences. The mean square differences are given in 4 sets: *A*, *B*, *C*, *D*. In set *B*, all 82 calculation stations were used. In set *A*, 4 slightly dubious stations on the right end of the observed profile were neglected. The central part of the observed profile was plainly irregular and reflecting the effects of shallow features not connected with the cap or salt. In *C*, therefore, the 15 central and the 4 northeast calculation stations at the right end were neglected. In *D*, the 15 central and the 4 calculation stations at the right end were weighted one; and the other 62 were weighted two.

The results I–IV are really the condensed final results; and V–VIII are the condensed next-to-the-last results.

A single line under I–VIII does not give a simultaneous series of mean squares respectively for $(b-e)$ et cetera. But if, for example, the line I-*A*-mean is referred to, then 2.80 was the least mean square which could be obtained for $(c-e)$ by varying the regional gradient within certain plausible limits. But for the regional gradient under which *ce* had a mean square of 2.80, the mean square of *cd* is greater than 3.00, of *cf* is greater than 3.57 et cetera. By varying the regional gradient, the mean square of *cd* could be brought down to 3.00, but no regional gradient was found by which it was possible to bring it down to 2.80, and so on for the other forms, *be*, *bf*, and *cf*.

The use of a small regional gradient toward the right gave distinctly better results than the use of no regional gradient.

Density assumption *A* gave the closest fit of calculated to observed gradient profile. The very slight change of the density assumptions to those of *B* or *C* greatly increased the size of the mean square for all combinations of (b, c)–(d, e, f). Density assumption *D* gave some small mean squares for the median but a large discrepancy between the median and the mean. The whole series of results under density assumption *D* showed the same discrepancy and also a combination of very small and very large differences between the observed and calculated profiles.

The two forms, *cd* and *ce*, were consistently the best two in all the calculations. Either *cd* or *ce* was first in all calculations made, and in the final series I–IV, these two forms held first and second places. In some of the earlier calculations, one of them, more commonly *ce*, was displaced from second to third place by *be*. The differ-

ence in those cases, however, was small between *ce* and *be*, 3.15 against 3.24; 3.43 against 3.50; 2.13 against 2.70; 2.69 against 3.24.

The relative standing of the various forms in reference to the order of occurrence of their respective mean squares is given in Tables II and III. In Table II, the "mean" mean squares and the median mean squares of the series, I–VIII, are given in order of their

TABLE II

Weight	*Means*	*Weight*	*Medians*
25	1.63 *ce*	25	1.17 *ce*
	1.65 *cd*		1.21 *cd*
	2.24 *cf*		2.30 *cd*
	2.29 *ce*		1.38 *cd*
	2.39 *be*		1.44 *ce*
20	2.42 *cd*	20	1.44 *ce*
	2.61 *cd*		1.50 *ce*
	2.71 *bf*		1.50 *cd*
	2.80 *ce*		1.59 *cf*
	2.80 *ce*		1.69 *cd*
15	2.85 *cd*	15	1.69 *cf*
	2.89 *cf*		1.90 *bf*
	2.99 *ce*		1.92 *be*
	2.99 *be*		1.94 *cf*
	3.00 *cd*		2.02 *cd*
10	3.26 *bf*	10	2.03 *be*
	3.36 *cd*		2.03 *cf*
	3.37 *be*		2.13 *be*
	3.40 *cf*		2.13 *be*
	3.46 *be*		2.17 *cd*
5	3.50 *be*	5	2.18 *be*
	3.53 *cd*		2.25 *bf*
	3.57 *cf*		2.40 *bf*
	3.69 *ce*		2.57 *cd*
	3.69 *bf*		2.69 *be*
0	3.87	0	2.70 *ce*
	3.90		2.73 *bf*
	3.94		3.24 *ce*
			3.24 *ce*
			3.50 *ce*

magnitude for the mean squares, less than 4.00 for the means, and 3.50 for the medians. The relative position of each form in regard to the magnitude of its mean square is given in Table II for the first 25 in each list. First place is ranked 25 and last place, 1.

Although strictly the least mean square should indicate the most probable set of assumptions, there is considerable probable error in our calculations and we can not be certain that the least mean square of our calculations actually is significantly less than some slightly larger mean square. Tables II and III give a study of the distribution

TABLE III

Means

be	*bf*	*cd*	*ce*	*cf*
21	18	24	25	23
12	10	20	22	14
8	1	19	17	7
6		15	16	3
5		11	13	
		9	2	
—	—	—	—	—
52	29	102	95	47

Medians

be	*bf*	*cd*	*ce*	*cf*
13	14	24	25	17
10	4	23	21	15
8	3	22	20	12
7		18	19	9
5		16		
1		11		
		6		
		2		
—	—	—	—	—
44	21	122	85	53

of the mean squares. And from them, conclusions can be drawn in regard to the relative probability of the five forms, *be*, *bf*, *cd*, *ce*, *cf*.

In absolute value of the mean square, *ce* takes first place over *cd* both in the means and the medians, but by so small a difference, 1.63 against 1.65, and 1.17 against 1.21, that it is presumably of no significance. The least mean square of any of the other three forms is 2.24 in the means and 1.59 in the medians. The difference seems significant.

In probability from frequency of placement and position of placement among the 25 highest mean squares of I–VIII, *cd* seems slightly more probable than *ce;* and *cd* and *ce* together are decisively more probable than *be*, *bf*, and *cf*. The form *cd* was placed 7 times against *ce*'s 6 times in the first 25 means, and 8 times against *ce*'s 4 times in the medians. The forms *be* and *cf* each held two places in the first 10 of the means, but otherwise *be*, *bf*, and *cf* were in the last 15; and in the medians of these three, only *cf* won a single place in the first 10. The sum of the positions of placement of each form gives a measure of its probable relative position in reference to the others. The form *cd*, therefore, would seem to be most probably first with *ce* a fairly close second. The forms *bc* and *cf* are almost tied for a poor third and fourth, with *cf* slightly in the lead and *bf* a poor fifth.

The value of *bd* runs close to that of *be*. It does not give any important information beyond that given by *be*. It was dropped from the calculations, therefore, in order to save time.

The relative order (*cd* and *ce*), (*be* and *cf*), *bf* is to be expected if there is overhang on both sides; for then

	Assumptions in regard to	
	Southwest Flank	*Northeast Flank*
cd and *ce*=	Approximately right	Approximately right
be=	Wrong	Approximately right
cf=	Approximately right	Wrong
bf=	Wrong	Wrong

CONCLUSIONS

The calculations from the torsion-balance survey at Barbers Hill indicate the presence of considerable overhang on the right and a smaller overhang on the left. The degree of probability of the indication is "good" for commerical purposes and fair for purely scientific purposes. If some important fundamental physical constant were being determined, and if the determination were to have to stand for a long time, the technique of the calculations should be refined yet further; and further tests should be made to see if some geologically possible set of assumptions would not give a lesser mean square than *cd* or *ce*. But in terms of the accuracy of commercial geological and geophysical work on which oil companies base leasing and drilling operations, the accuracy of the indication from these calculations is good.

The results of the calculations also give a fair indication that there is much more overhang on the northeast than on the southwest. From the small differences between the mean squares of *ce* and *cd* and the much larger difference between those mean squares and the mean squares of *cf*, it would seem probable that the actual position of the edge of the salt would lie between *d* and *e*. From the closeness of the mean squares of *be* and *cd* (and *ce*), it seems probable that the actual position of the edge of the salt lies considerably nearer *c* than *b* and that it might lie even slightly inside of *c*, although it looks improbable that the edge of the salt could lie far inside of *c*.

How much further the accuracy of this type of calculation and prediction can be carried by more refined technique is an open question. It should be possible to obtain a little higher accuracy than that of the calculations of this study. The calculations another time could be done in a way to reduce the probable error of calculating. Added corrections could be made, as, for example, for the aureole of upturned beds. If the field stations were laid out better for the purpose and the observations taken with extraordinary care, the basic original data would be more accurate. But in attempting to obtain better

quantitative accuracy, the method would be forced well toward the limit of its accuracy.

A limiting factor comes in to affect quantitative calculations. The salt effect is small. The effect of deficiencies of salt (for example, in an overhang) is yet smaller. Within certain limits, it is impossible for us to determine in our calculations whether the deficiency of salt (which forms the overhang) is spread vertically up and down the edge of the salt, or whether it is mainly high or mainly low. The writer therefore would hesitate about attempting to push the quantitative predictions much further. Yet in some cases, for commercial purposes, it might be worth while to know whether there was a 1-to-4 chance of greater width of the overhang than was commonly believed.

The degree of success of the calculations at Barbers Hill indicates that this type of calculation might be successful in the determination of overhang on other domes. Barbers Hill is a fairly good dome for such calculations as the terrane is good for torsion-balance observations; the dome is far enough inland from the coast so that the density of the sediments is not too low, and a fair amount is known about the form of the cap rock. The calculations will become tedious and more inaccurate for domes on which there are only a few wells drilled into the cap and salt. The accuracy, also, will probably not be as good for domes nearer the coast as for those farther inland, for there is a thicker section of light sediments near the coast.

An advantage of this torsion-balance method over the suggested seismic method of determination of overhang is that the torsion-balance method is independent of any flank wells. The calculations could be made if there were only one well on the dome, if that well went through the cap into the salt. It would require much less time and be more satisfactory, however, to have more data in regard to the top of the cap. But flank wells are in no way necessary to the torsion-balance calculations.

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EFFECT OF ANISOTROPY ON APPARENT RESISTIVITY CURVES[1]

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ABSTRACT

The anisotropic character of the sedimentary formations is a fact which has been so far generally overlooked in the interpretation of resistivity curves. The purpose of the present article is to indicate the normal distortion of the resistivity-depth curves for non-homogeneous horizontal stratified conditions. Two cases are investigated, namely where the anisotropies of the individual layers are the same and where they assume different values. The amount of error made in the accepted methods of interpretation is also indicated. The writer proposes a method of interpreting three-layer resistivity curves when due allowance is made for the anisotropic conditions of the ground.

A practical case illustrates the method.

INTRODUCTION

The anisotropic character of the sedimentary formations is a fact which has been, so far, generally overlooked in the interpretation of resistivity curves. The distortion of the electrode spacing-apparent resistivity curves by non-homogeneous conditions of the individual layers accounts for the numerous empirical methods of interpretation. Gish and Rooney (1)[3] proposed, as a first approximation, to interpret the depth to horizontal discontinuities as being equal to the electrode separation at which a point of maximum curvature is obtained in the resistivity curve. Schlumberger (2) estimates the depth as being three-fourths of the same distance. Lancaster-Jones (3) proposed a closer approximation for the depth by taking two-thirds of the electrode spacing for which an inflection point occurs in the resistivity curve. However, by virtue of the nature of such a point which lies on a practically straight part of the curve, the depth determination may be erroneous. The closest approximation in depth determination was obtained by Tagg (4) who really advocated a mathematical solution of the resistivity curve by making use of nomographic charts accurately determined from the formula of the apparent resistivity

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[3] Numbers in parentheses indicate references at end of this article.

in the case of two plane boundaries. Tagg, however, stressed the point that before his method could be applied, the ground under investigation must satisfy the hypothesis at the base of the establishment of the charts; mainly, the individual layers must be homogeneous and isotropic. A misleading extension of Tagg's method to the interpretation of the three-layer resistivity curves has been proposed by Manhart (5) and Tattam (6), since they actually overlook the ground condition in their method. The author of the present article proposes here a "successive approximation method" for the extension of Tagg's two-layer method to the case of three horizontal layers. However, the ground under investigation must be homogeneous and isotropic or at least the individual layers must have the same coefficient of anisotropy.

Consequently, the method is best applicable to the determination of depth to bed rock, igneous or vertically stratified, under a cover of placer or gravel beds. The method can also be advantageously applied to the determination of thickness of limestone beds, lava flows, et cetera. An example of application of the writer's method is indicated here, together with the indication of the correction to be applied in order to compensate for the anisotropy of the ground.

ANISOTROPY OF SEDIMENTARY LAYERS

The effect of anisotropy on the apparent resistivity has been mentioned only a few times in the geophysics literature by Maillet and Doll (7), Slichter (8), and Mülier (9).

It is generally accepted that in stratified media the conductivity is larger parallel with the bedding plane than perpendicular to the stratification, the mobility of the ions being larger parallel with the schistosity than at right angles to it. However, if the apparent resistivity ρa of such a stratified ground be measured with the aid of four equidistant contacting electrodes, the outside ones being the current electrodes, and the inside ones the potential electrodes (Wenner-Gish-Rooney set-up), the formula,

$$\rho_a = 2\pi a \frac{V}{I},$$

where

a = electrode spacing
V = potential at the inside electrodes
I = current at the outside electrodes,

gives larger apparent resistivities ρa parallel with the bedding surfaces than perpendicular to them. The explanation of this paradox is beyond the scope of the present paper, but a few practical results are given.

Measurements were made on sedimentary beds *in situ* using one-foot electrode separation.

An outcrop of hard broken clay (10 feet thick), slightly stratified, of the Laramie formation (Tertiary) in Golden, Colorado, has given the following results.

Resistivity parallel with the bedding surface: 825 ohm feet
Resistivity perpendicular to the bedding surface: 388 ohm feet

A hard laminated shale interbedded with sandstone of the Benton formation (Tertiary) in Golden gave the following results.

Resistivity parallel with the bedding surface:
Electrodes in sandstone seam: 3,000 ohm feet
Electrodes in shaly seam: 1,760 ohm feet
Resistivity perpendicular to the bedding plane:
204 ohm feet

Another series of measurements was made at the same location on a laminated fine white sandstone (Benton formation) and the following results were obtained.

Resistivity parallel with the bedding plane: 1,770 ohm feet
Resistivity perpendicular to the bedding plane: 970 ohm feet

From the preceding results, one should not generalize that the large axis of the anisotropy ellipse will always be in the stratification plane; actually, jointing in shales may produce an anomalous anisotropy. It is thus possible for the conductivity to be larger perpendicular to, than parallel with, the stratification. The anisotropy coefficient α of sedimentary formations which is defined as the ratio of the apparent parallel resistivity to the apparent normal resistivity may then assume values ranging from close to zero to values as high as ten. The isotropic conditions of a layer are represented by $\alpha = 1$.

ANISOTROPY REDUCTION THEOREM

The resistivity method of prospecting being a surface potential method, it is necessary to investigate the distribution of potential in an anisotropic medium in order to calculate the apparent resistivity. Let us consider the case of two superimposed layers designated by the indexes 1 and 2 and of anisotropy coefficients $\alpha 1$ and $\alpha 2$. The resistivities perpendicular to the stratification are designated by ρ_{1v} and ρ_{2v} and the resistivities parallel with the bedding planes by ρ_{1A} and ρ_{2A} which latter resistivities may generally be assumed to be

constant in any horizontal direction due to the continuity of character of sedimentary formations parallel with the bedding surfaces. Thus we have:

$$\frac{\rho_{1h}}{\rho_{1v}} = \alpha_1 \quad \text{and} \quad \frac{\rho_{2h}}{\rho_{2v}} = \alpha_2$$

Suppose that the current is introduced at the surface at two points C_1 and C_2 (Fig. 1). The densities of current across surfaces

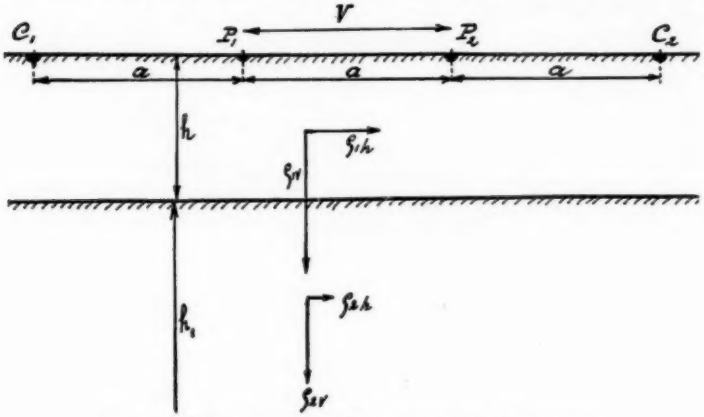

FIG. 1.—Gish-Rooney electrode set-up and resistivity vectors.

perpendicular to the axes OX, OY, and OZ are respectively:

$$i_x = -\frac{1}{\rho_{1h}} \times \frac{\partial V_1}{\partial x}$$

$$i_y = -\frac{1}{\rho_{1h}} \times \frac{\partial V_1}{\partial y}$$

$$i_z = -\frac{1}{\rho_{1v}} \times \frac{\partial V_1}{\partial z},$$

when the axis OZ is chosen perpendicular to the bedding plane XOY in which the axes ox and oy may have any particular position. V_1 is the electrical potential at any point in medium 1 and i_x, i_y and i_z the densities of current perpendicular to the directions x, y, and z at that point.

The total current at the point considered is then given by

$$I = ii_x + ji_y + ki_z$$

where i, j and k are unit vectors taken along the axes ox, oy, and oz. Since we must have conservation of the vector current, we find that the divergence of I is zero:

$$\nabla \cdot I = -\left(\frac{1}{\rho_{1h}}\frac{\partial^2 V_1}{\partial x^2} + \frac{1}{\rho_{1h}}\frac{\partial^2 V_1}{\partial y^2} + \frac{1}{\rho_{1v}}\frac{\partial^2 V_1}{\partial z^2}\right) = 0$$

Thus Laplace's equation in the anisotropic medium considered becomes:

$$\frac{1}{\rho_{1h}}\left(\frac{\partial^2 V_1}{\partial x^2} + \frac{\partial^2 V_1}{\partial y^2}\right) + \frac{1}{\rho_{1v}}\frac{\partial^2 V_1}{\partial z^2} = 0$$

If we substitute in this equation

$$x = \xi\sqrt{\frac{1}{\rho_{1h}}}$$

$$y = \eta\sqrt{\frac{1}{\rho_{1h}}}$$

$$z = \zeta\sqrt{\frac{1}{\rho_{1v}}}$$

we obtain the equation:

$$\frac{\partial^2 V_1}{\partial \xi^2} + \frac{\partial^2 V_1}{\partial \eta^2} + \frac{\partial^2 V_1}{\partial \zeta^2} = 0,$$

which is the ordinary Laplace's equation. We have thus reduced the space xyz into a space ξ, η, ζ in which Laplace's equation is satisfied but where the dimensions are expanded by the factor $\sqrt{\rho_{1h}}$ in the horizontal directions and $\sqrt{\rho_{1v}}$ in the vertical direction.

If we leave the vertical dimensions unchanged, the horizontal dimensions of the space x, y, z, are then expanded by a factor

$$\sqrt{\frac{\rho_{1h}}{\rho_{1v}}} = \sqrt{\alpha_1}$$

in order to obtain a medium ξ, η, ζ in which Laplace's equation is satisfied. Thus we have the transformation:

I.
$$\xi = x\sqrt{\alpha_1}$$
$$\eta = y\sqrt{\alpha_1}$$
$$\zeta = z.$$

The medium ξ, η, ζ obtained by the preceding transformation of coördinates will be rendered homogeneous by making the following substitutions for the horizontal and vertical resistivities.

$$\rho'_{1h} = \rho_{1h} \frac{1}{\sqrt{\alpha_1}}$$

$$\rho'_{1v} = \rho_{1v} \sqrt{\alpha_1}$$

where ρ'_{1h} and ρ'_{1v} are the resistivities parallel with, and perpendicular to, the bedding surface in the medium ξ, η, ζ.

Similarly the medium 2 will be reduced to homogeneous conditions by the following transformation:

II.

$$\xi' = x\sqrt{\alpha_2}$$

$$\eta' = y\sqrt{\alpha_2}$$

$$\zeta' = z$$

$$\rho''_{2h} = \rho_{2h} \frac{1}{\sqrt{\alpha_2}}$$

$$\rho''_{2v} = \rho_{2v} \sqrt{\alpha_2}$$

In order that the points at infinity in medium 2 shall correspond with the points at infinity in medium 1, it is necessary to expand the medium ξ', η', ζ' by the factor $\sqrt{\frac{\alpha_1}{\alpha_2}}$, horizontal and vertical dimensions as well. The transformation II becomes:

III.

$$\xi = x\sqrt{\alpha_1}$$

$$\eta = y\sqrt{\alpha_1}$$

$$\zeta = z\sqrt{\frac{\alpha_1}{\alpha_2}}$$

$$\rho'_{2h} = \rho_{2h} \frac{\sqrt{\alpha_1}}{\alpha_2}$$

$$\rho'_{2v} = \rho_{2v} \sqrt{\alpha_1}$$

We have thus reduced media 1 and 2 to a single system of coordinates ξ, η, ζ in which we have homogeneous and isotropic con-

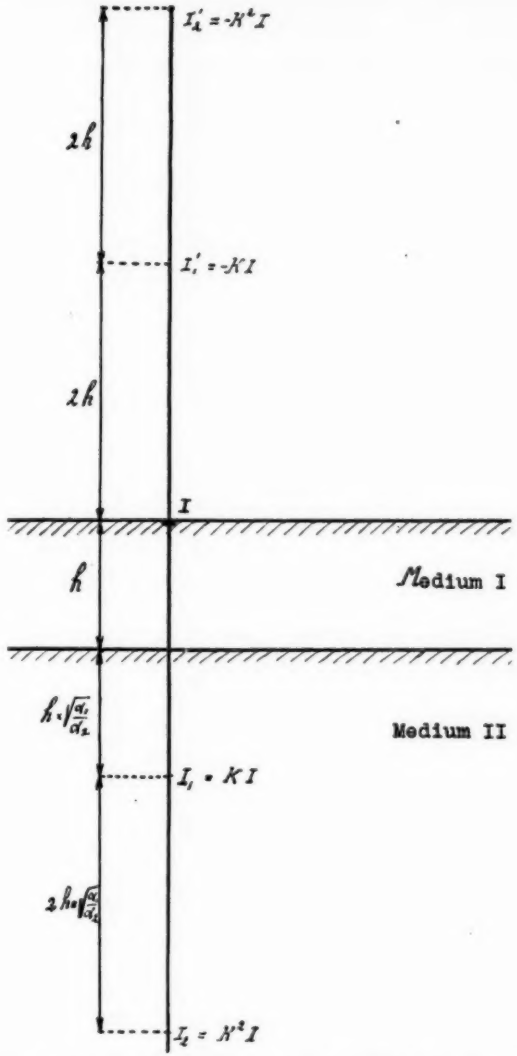

FIG. 2.—Electrical images for two media of different anisotropies.

ditions. Consequently the formulae of the apparent resistivity which have been established by Hummel (10) for homogeneous and isotropic layers can be easily extended to the anisotropic media considered here. We notice first that the reflection coefficient or resistivity factor

$$K = \frac{\rho'_{2v} - \rho'_{1v}}{\rho'_{2v} - \rho'_{1v}}$$

which governs the intensities of the electrical images has not changed. We will then calculate the potential at a point of coördinates ξ, η, o on the surface of the ground (Fig. 2) when a current I is introduced into the ground at the origin of the system of coördinates. In order to facilitate the calculations, the dimensions in medium 2 are expressed as functions of the coördinate system ξ', η', ζ'.

Thus the electrical potential due to I at the point (ξ, η, o) is given by:

$$V = \frac{I\rho'_{1v}}{2\pi}\left[\frac{1}{\sqrt{\xi^2+\eta^2}} + \sum_{n=1}^{n=\infty} K^n \frac{1}{\sqrt{\xi^2+\eta^2+(2nh)^2}} + \sum_{n=1}^{n=\infty} \frac{K^n}{\sqrt{\xi^2+\eta^2+\left\{h\left[1+(2n-1)\sqrt{\frac{\alpha_1}{\alpha_2}}\right]\right\}^2}}\right]$$

Expressing now ξ and η as functions of the original coördinates x and y, we obtain:

$$V = \frac{I\rho'_{1v}}{2\pi}\left[\frac{1}{\sqrt{(x^2+y^2)\alpha_1}} + \sum_{n=1}^{n=\infty} \frac{K^n}{\sqrt{(x^2+y^2)\alpha_1+(2nh)^2}} + \sum_{n=1}^{n=\infty} \frac{K^n}{\sqrt{(x^2+y^2)\alpha_1+\left[1+(2n-1)\sqrt{\frac{\alpha_1}{\alpha_2}}\right]^2 h^2}}\right]$$

If we consider now the Wenner-Gish-Kooney set-up of electrodes as given in Figure 1 and choose the x axis as the electrode line, the difference of potential at the inside electrodes due to the current I flowing through the outside electrodes is given by:

$$V_{P_1} - V_{P_2} = \frac{I'\rho_{1v}}{2\pi}\left[\frac{1}{a\sqrt{\alpha_1}} + 2\sum_{n=1}^{n=\infty} K^n \left\{\frac{1}{\sqrt{a^2\alpha_1+(2nh)^2}}\right.\right.$$

$$- \frac{1}{\sqrt{4a^2\alpha_1 + (2nh)^2}} \Bigg\}$$

$$+ 2 \sum_{n=1}^{n=\infty} K^n \left\{ \frac{1}{\sqrt{a^2\alpha_1 + \left[1 + (2n-1)\sqrt{\frac{\alpha_1}{\alpha_2}}\right]^2 h^2}} \right.$$

$$\left. - \frac{1}{\sqrt{4a^2\alpha_1 + \left[1 + (2n-1)\sqrt{\frac{\alpha_1}{\alpha_2}}\right]^2 h^2}} \right\} \Bigg]$$

The formula for the apparent resistivity in this case is given by:

$$\rho_a = 2\pi a \sqrt{\alpha_1} \frac{V_{P_1} - V_{P_2}}{I}$$

in the ξ, η, ζ system as a function of the distance a measured in the xyz system.

Thus the relative apparent resistivity $\frac{\rho_a}{\rho'_{1v}}$ for the case of two non-homogeneous layers is given by:

IV.

$$\frac{\rho_a}{\rho'_{1v}} = 1 + 2 \sum_{n=1}^{n=\infty} K^n \left\{ \frac{1}{\sqrt{1 + \left(2n \frac{h}{a\sqrt{\alpha_1}}\right)^2}} \right.$$

$$\left. - \frac{1}{\sqrt{4 + \left(2n \frac{h}{a\sqrt{\alpha_1}}\right)^2}} \right\}$$

$$+ 2 \sum_{n=1}^{n=\infty} K^n \left\{ \frac{1}{\sqrt{1 + \left[1 + (2n-1)\sqrt{\frac{\alpha_1}{\alpha_2}}\right]^2 \left(\frac{h}{a\sqrt{\alpha_1}}\right)^2}} \right.$$

$$\left. - \frac{1}{\sqrt{4 + \left[1 + (2n-1)\sqrt{\frac{\alpha_1}{\alpha_2}}\right]^2 \left(\frac{h}{a\sqrt{\alpha_1}}\right)^2}} \right\}$$

It is well to stress the point that ρ'_{1v} represents the resistivity of the homogeneous top layer corresponding with the anisotropic case under investigation and that in order to obtain comparable resistivity

curves the ratio $\frac{\rho_a}{\rho'_{1v}}$ or the relative apparent resistivity will be studied as a function of the relative depth $\frac{h}{a}$.

A few applications of the theorem of the reduction of anisotropic conditions to homogeneous conditions are considered here.

APPLICATIONS

1. TWO STRATA OF THE SAME ANISOTROPY

If we suppose that the anisotropy coefficients α_1 and α_2 are equal, formula IV reduces to the simpler form:

$$\frac{\rho_a}{\rho'_{1v}} = 1 + 4\sum_{n=1}^{n=\infty} K^n \left\{ \frac{1}{\sqrt{1+\left(2n\frac{h}{a\sqrt{\alpha_1}}\right)^2}} - \frac{1}{\sqrt{4+\left(2n\frac{h}{a\sqrt{\alpha_1}}\right)^2}} \right\} \qquad \text{V.}$$

From this formula, we calculated the relative apparent resistivity $\frac{\rho_a}{\rho'_{1v}}$ for the following cases.

1) $\alpha_1 = 1$ Isotropic conditions
2) $\alpha_1 = 2$ Condition which is often obtained for sedimentary beds
3) $\alpha_1 = 4$ Condition obtained for intense compaction and dynamo-metamorphism

We further assumed the following resistivities and thicknesses.

$$\rho_{1v} = 2 \qquad h = 4$$

$$\rho_{2v} = 0 \qquad h_1 = \infty$$

By carrying out the calculations indicated by formula V, the resistivity curves *a*, *b*, and *c* in Figure 3 are obtained using as coördinates the relative resistivity ρ_a/ρ'_{1v} and the relative electrode spacing h/a. The curves obtained for $\alpha_1 = 0.5$ and $\alpha_1 = 0.25$ are also indicated in Figure 3, although such conditions are seldom encountered in field practice.

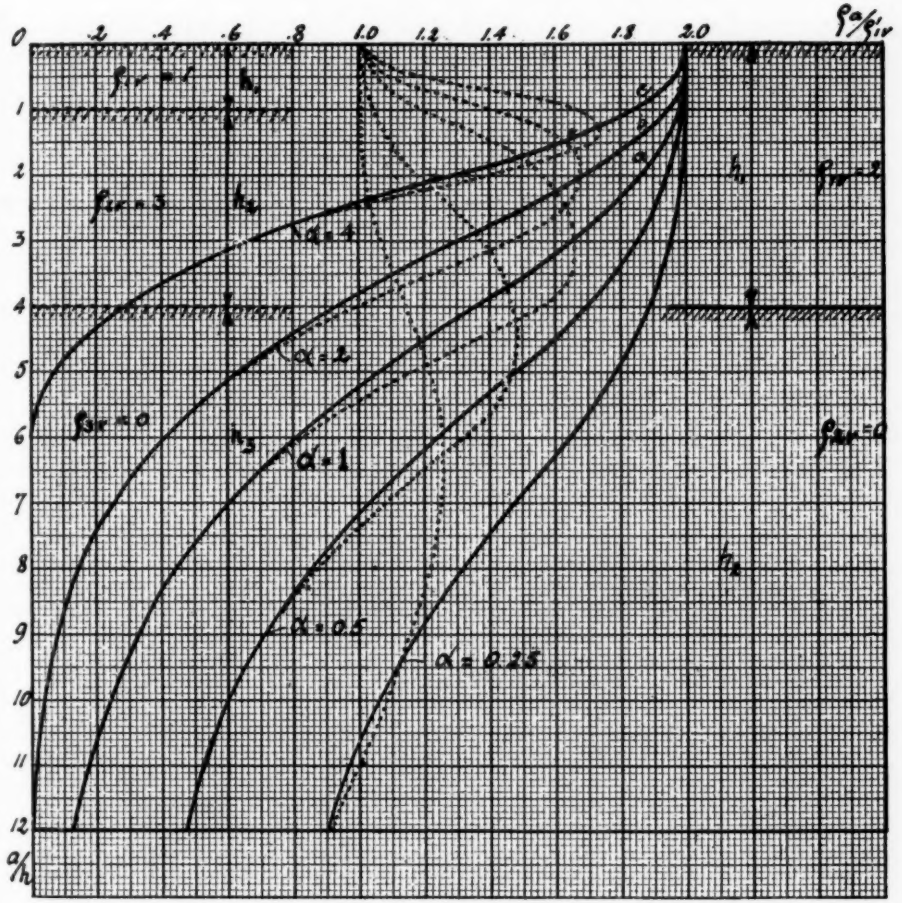

FIG. 3.—Theoretical resistivity curves. Right: two-layer case. Left: three-layer case.

2. THREE STRATA OF SAME ANISOTROPY

The theory previously given for a two-layer case can be easily extended to the three-layer case when the individual layers present the same anisotropy. It can be easily proved that the expression of the apparent resistivity in such a case is given by:

$$\frac{\rho_a}{\rho'_{1v}} = 1 + 4\sum_{n=0}^{n=\infty} K^{n+1} \left\{ \frac{1}{\sqrt{1 + \left[2(n+1)\frac{h}{a\sqrt{\alpha}}\right]^2}} - \frac{1}{\sqrt{4 + \left[2(n+1)\frac{h}{a\sqrt{\alpha}}\right]^2}} \right\}$$

$$+ 4(1 - K^2)K_1 \sum_{n=0}^{n=\infty} (n+1)K^n \left\{ \frac{1}{\sqrt{1 + \left[2\frac{h_1}{a\sqrt{\alpha}} + \left\{2(n+1)\frac{h}{a\sqrt{\alpha}}\right\}\right]^2}} - \frac{1}{\sqrt{4 + \left[2\frac{h_1}{a\sqrt{\alpha}} + \left\{2(n+1)\frac{h}{a\sqrt{\alpha}}\right\}\right]^2}} \right\}$$

$$+ 4(1 - K^2)K_1^2 \sum_{n=0}^{n=\infty} \left[\frac{n(n+1)(1-K^2)}{2} - (n+1)K^2\right] K^{n-1} \left\{ \frac{1}{\sqrt{1 + \left[4\frac{h_1}{a\sqrt{\alpha}} + 2(n+1)\frac{h}{a\sqrt{\alpha}}\right]^2}} - \frac{1}{\sqrt{4 + \left[4\frac{h_1}{a\sqrt{\alpha}} + 2(n+1)\frac{h}{a\sqrt{\alpha}}\right]^2}} \right\}$$

$$+ 4(1 - K^2)K_1^3 \sum_{n=0}^{n=\infty} \left[\sum_{m=0}^{n} \frac{(m-1)m}{2} (1 - K^2)^2 - n(n+1)(1-K^2)K^2 + (n+1)K^4 \right] K^{n-2}$$

$$\left\{\frac{1}{\sqrt{1+\left[6\frac{h_1}{a\sqrt{\alpha}}+2(n+1)\frac{h}{a\sqrt{\alpha}}\right]^2}}-\frac{1}{\sqrt{4+\left[6\frac{h_1}{a\sqrt{\alpha}}+2(n+1)\frac{h}{a\sqrt{\alpha}}\right]^2}}\right\}$$

$$+\ \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$

where $K=\dfrac{\rho_{2v}-\rho_{1v}}{\rho_{2v}+\rho_{1v}}$ and $K_1=\dfrac{\rho_{3v}-\rho_{2v}}{\rho_{3v}+\rho_{2v}}$

h and h_1 are respectively the thicknesses of the top and intermediate layer, the third layer having an infinite thickness.

The resistivity curves have been calculated for the following conditions:

$\rho_{1v}=1$ $\quad$ $h=1$

$\rho_{2v}=3$ $\quad$ $h_1=3$

$\rho_{3v}=0$ $\quad$ $h_2=\infty$

and for the following anisotropy coefficients:

$$\alpha=4,\ 2,\ 1,\ 0.5 \text{ and } 0.25$$

For large electrode spacings, the average resistivity of the two top layers can be calculated by Kirchhoff's law for two resistances connected in parallel. This average resistivity is precisely 4 here, and for large electrode spacings the three-layer case is reduced to the two-layer case previously investigated. This facilitates considerably the numerical computations since for increasing relative electrode separation the three-layer curves and the two-layer curves are tangent and finally superimposed. The results obtained are plotted in Figure 3.

By considering the curves in Figure 3, the following conclusions for a three-layer curve can be arrived at.

1. Anisotropies of sedimentary beds larger than one, shift the points of maximum curvature toward smaller electrode spacings and the greater the anisotropy the larger the amount of displacement.

2. Anisotropic ground conditions ($\alpha<1$) reduce the anomaly in the resistivity curve and the smaller the anisotropy coefficient, the larger the reduction. For anisotropy coefficient α larger than 1, the anomaly is increased and the curves are flattened. This is a fairly general condition encountered in field practice.

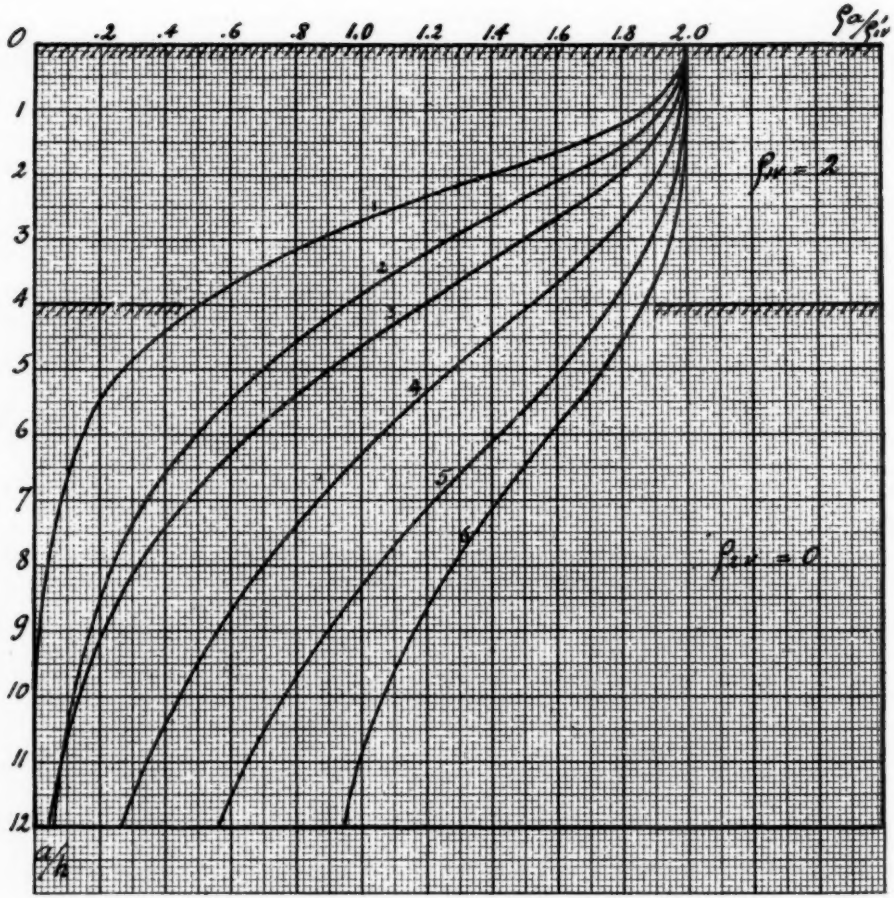

FIG. 4.—Theoretical resistivity curves for different individual anisotropies.

1. $\alpha_1 = 4$, $\alpha_2 = 2$
2. $\alpha_1 = 2$, $\alpha_2 = 4$
3. $\alpha_1 = 2$, $\alpha_2 = .5$
4. $\alpha_1 = 1$, $\alpha_2 = .25$
5. $\alpha_1 = 5$, $\alpha_2 = .25$
6. $\alpha_1 = .25$, $\alpha_2 = .5$

3. The application of Tagg's method of interpretation to depth determination gives a solution which is multiplied by a factor equal to the square root of the anisotropy coefficient.

4. The Gish-Rooney rule of depth determination is approximately verified when the anisotropy coefficient α equals $1/2$.

3. TWO STRATA OF DIFFERENT ANISOTROPIES

This case has been investigated previously and formula IV gives the value of the relative apparent resistivity. In order to obtain an idea of the amount of deviation in the resistivity curve produced by the presence of anisotropy we have computed the apparent resistivity curves for the following two-layer case.

$$h = 4 \qquad \rho_{1v} = 4$$
$$h_1 = \infty \qquad \rho_{2v} = 0$$

and for different combinations of the anisotropy coefficients α_1 and α_2 as shown in Figure 4.

Comparative studies of the two-layer curves in Figures 3 and 4 indicate that the anisotropy of the surface layer governs the general outline of the apparent resistivity curve; however, it appears rather impractical to compute a correcting factor for the depth determination. Considering the theory and the results obtained in the case of different anisotropies for a horizontally stratified ground, it appears that a determination of the depth to horizontal discontinuities can not be obtained by application of Tagg's method of interpretation.

Furthermore, the extension of the method to the solution of three-layer problems as proposed by Manhart and Tattam may lead to considerable error since in many cases it is not less than imposing a solution on the problem.

In order to minimize the chances of errors in interpreting the three-layer resistivity curves, the writer proposes the method outlined in the following paragraphs for the interpretation of homogeneous or equally anisotropic layers.

INTERPRETATION OF THREE-LAYER CURVES

For the interpretation of resistivity curves when Tagg's charts are applied to the solution of a three-layer case, the writer of the present article proposes the following "Successive Approximation method" for which the steps are as follows.

1. Average the resistivities of the surface for electrode spacings from 5 to 20 feet, which will give a value of the resistivity of the top layer ρ_1. Very careful measurements must be made in the field and

precautions should be taken in order that the depth of penetration of the electrode stakes shall not exceed 1/5 of the electrode spacings. It is recommended that measurements be made for different values of the current, and of the commutating frequency. Since the value of the method depends greatly on the accuracy with which the resistivity of the top layer is known, too much precaution can not be taken in this determination.

2. ρ_1 is plotted to scale on the resistivity axis and a line drawn from ρ_1 to meet tangentially the first part of the curve.

3. Resistivities are read for several electrode spacings on the curve just drawn and Tagg's method is applied to that first part of the curve. The process yields the resistivity of the second layer ρ_2, the thickness of the first layer h_1, and the resistivity factor $K_1=\frac{\rho_2-\rho_1}{\rho_2+\rho_1}$.

4. The depth to the third layer is estimated by Lancaster-Jones' method. Thus $h_1+h_2=\frac{2}{3}d$ where d is the distance to the inflection point comprised between the two lower maximum curvature points.

5. The apparent or average resistivity ρ'_1 of the two layers of resistivities ρ_1 and ρ_2 in parallel is calculated by the formula:

$$\frac{h_1+h_2}{\rho'_1}=\frac{h_1}{\rho_1}+\frac{h_2}{\rho_2}$$

6. Tagg's method is then applied to the bottom part of the curve. A more accurate depth h'_2 than the one previously estimated is then obtained by tracing the curve's depth-resistivity factor. When they converge in a small area, the depth $h_1+h'_2$ and the resistivity factor $K_2=\frac{\rho_3-\rho_2}{\rho_3+\rho_2}$ are known with a fair degree of accuracy. From this expression of K_2, the value of the resistivity ρ_3 of the lower medium supposedly of infinite vertical extent can be calculated.

7. If the degree of accuracy with which $h_1+h'_2$ is known is not sufficient, the process may be recalculated once more by using $h_1+h'_2$ instead of $\frac{2}{3}d$ in the calculation of the average resistivities of the two top layers. A value ρ''_1 will be obtained and a more accurate value $h_1+h''_2$ will be found for the depth to the third layer. In other words, the mathematical process known as the "Successive Approximation method" is proposed.

A practical example worked from an actual resistivity curve is given here.

The problem is one of water-table determination which was worked by Tattam (curve 26) in the Newman district (New Mexico).

It is a typical three-layer curve (Fig. 5) with some irregularities of the order of the errors of observation expected with the equipment in use. They are then smoothed out before calculations. The determinations were made in an area underlain by valley fill and at about 2 miles from two wells which encountered water at 271 feet. Consequently the cone of exhaustion did not reach the region where the measurements were taken.

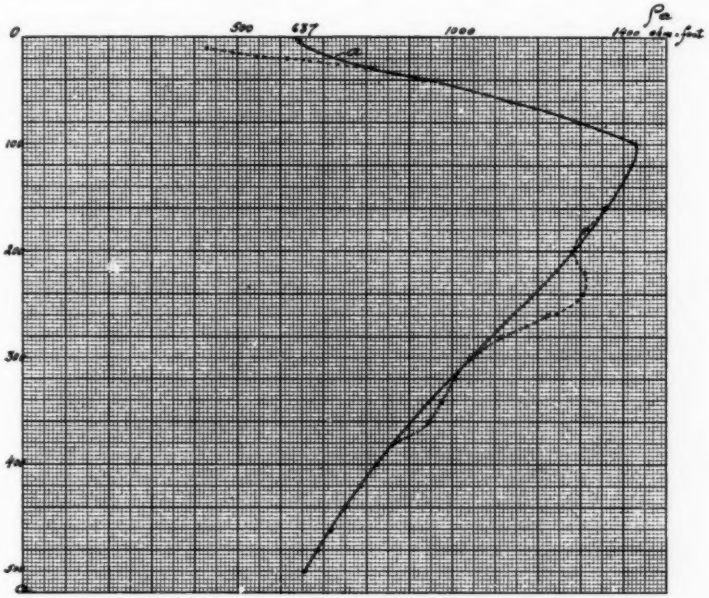

FIG. 5.—Apparent resistivity-electrode spacing curve.
- - - - Actual data.
——— Graphic approximation curve.

According to the method developed in the present article the three top values of the resistivities are averaged, which gives $1/3(428+611+932)=\rho'_1=637$ ohm feet for the resistivity of the top layer. The graphic approximation curve a is then traced, which meets the original curve tangentially. This curve is used to determine the thickness of the upper layer by the application of Tagg's method. The tabulation then obtained is shown in Table I.

The curve's depth-resistivity factors plotted from Table I on Figure 6 converge in a rather small area and consequently the depth

TABLE I

a	10	20		40		60		80		100	
$\rho'_1/\rho a$ ↓ K_1	.982	.920		.718		.582		.505		.463	
		h_1/a	h_1	h_1/a	h_1	h_1/a	h_1	h_1/a	h_1	h_1/a	h_1
0.1	No Intersection	.576	15.2	—	—	—	—	—	—	—	—
0.2		.920	18.4	.228	9.5	—	—	—	—	—	—
0.3		1.17	23.4	.45	18.0	.156	9.3	—	—	—	—
0.4		1.33	26.6	.588	23.5	.331	19.9	.190	15.2	.088	8.8
0.5		1.51	30.2	.709	28.3	.436	26.1	.323	25.8	.253	25.3
0.6		1.625	32.5	.799	31.9	.540	32.4	.422	33.7	.357	35.7
0.7		1.765	35.5	.889	35.6	.621	36.6	.497	39.8	.433	43.3
0.8		1.835	36.7	.969	38.7	.700	42.0	.579	46.3	.510	51.0
0.9		1.095	38.1	1.039	41.5	.770	46.0	.648	51.8	.578	57.8
1.0		2.00	40.0	1.118	44.8	.834	50.0	.707	56.4	.640	64.0

determination to the second layer may be considered as very good. We have: $h_1 = 33$ feet and $K_1 = 0.6$. Thus the value of the resistivity of the second layer is $\rho_2 = \rho'_1 \left(\frac{1+K_1}{1-K_1}\right) = 2{,}630$ ohm feet. By mak-

making use of the inflection point on the lower part of the curve situated approximately at the electrode spacing 300 feet, the total thickness of the two top layers is estimated at $h_1+h_2 = \frac{2}{3}\ 300 = 200$

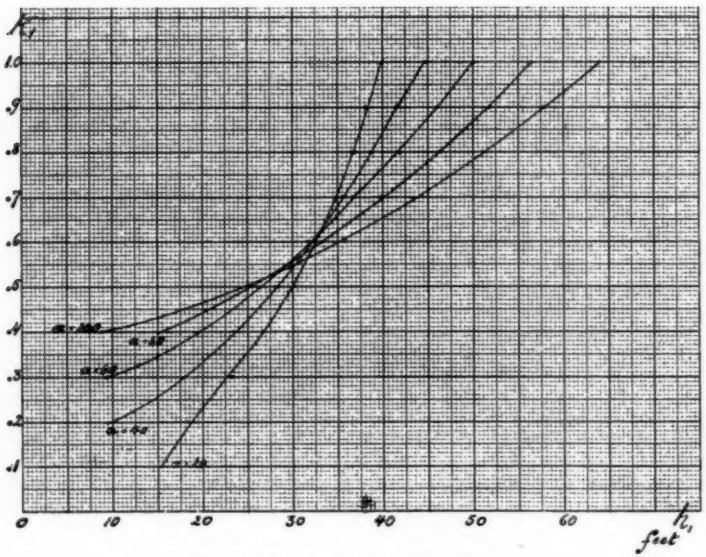

FIG. 6.—Depth-resistivity factor curves.

TABLE II

a	240		260		280		300		320		340		360		380	
$K_2\downarrow$ $\rho a/\rho'_1 \rightarrow$	.712		.663		.624		.595		.566		.541		.517		.492	
0.1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0.2	.251	60.5	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0.3	.472	113	.395	106	.323	90	.265	80	.184	59	.084	28.6	—	—	—	—
0.4	.616	147	.532	138	.475	133	.440	132	.399	128	.362	123	.325	117	.284	108
0.5	.719	172	.637	166	.580	160	.544	163	.507	162	.474	161	.446	161	.414	157
0.6	.811	195	.730	190	.673	189	.635	191	.596	191	.566	192	.539	190	.508	193
0.7	.882	212	.800	208	.742	208	.704	211	.664	212	.630	214	.600	216	.569	216
0.8	.939	226	.856	223	.799	224	.763	229	.724	232	.695	236	.670	241	.640	243
0.9	1.0	240	.910	238	.850	238	.812	244	.774	248	.746	254	.720	259	.691	262
1.0	1.05	252	.960	250	.903	252	.869	261	.832	266	.800	272	.776	279	.746	283

feet. Thus $h_2 = 200 - 33 = 167$ feet. The average resistivity of the two upper layers in parallel is then given by $\frac{200}{\rho'_1} = \frac{33}{657} + \frac{167}{2630}$ and $\rho'_1 = 1{,}755$ ohm feet. By the application of Tagg's charts to the lower part of the curve, Table II is obtained.

The depth-resistivity factor curves computed from Table II give a good area of convergence (Fig. 7) for which the coördinates are $h_1 + h'_2 = 187$ feet and $K_2 = 0.58$. The value of the resistivity of the lower medium is obtained by

$$\rho_3 = 1755 \frac{.42}{1.58} = 467 \text{ ohm feet}$$

If a better approximation for the depth to the third layer is desired, the process may be reworked using 187 feet instead of 200 for the

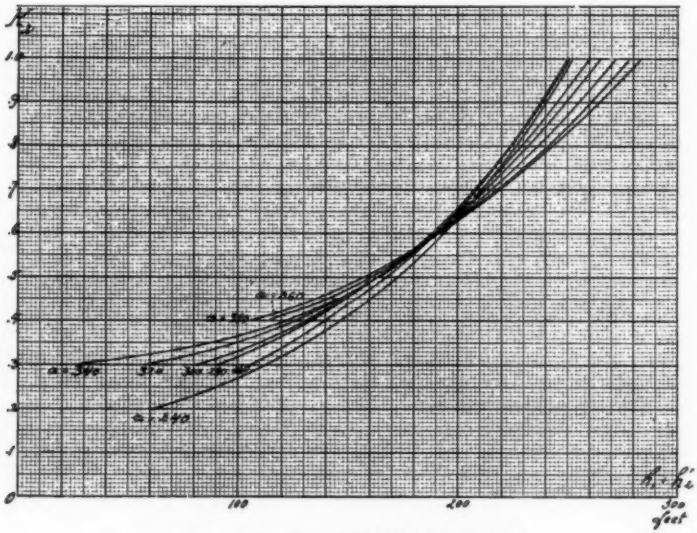

FIG. 7.—Depth-resistivity factor curves.

calculation of the average resistivity of the two upper layers. In general, however, one determination should give a close enough approximation.

If one takes pains to consider the curves given in Figure 3 and compares them with the outline of the curve in Figure 5, one notices

that the resistivity anisotropy in the present case can be estimated at approximately 2; consequently the depth to the water table can be estimated to be approximately $187 \times \sqrt{2} = 264$ feet, whereas Tattam and Manhart's method places the water table at 190 feet.

CONCLUSIONS

The present method of interpretation offers a means of solving completely a three-layer resistivity curve, the resistivities and thicknesses of the individual layers being obtained. The method permits the obtaining of results with an acceptable probable error of 5–10 per cent when the field and ground conditions fulfill the requirements of the theory of apparent resistivity for a horizontally stratified medium. The isotropy or equal anisotropy of the individual layers is a necessary condition for the application of this method. If no converging point is obtained in steps 3 and 6 of the present method, it is an indication that the anisotropies of the three layers are different, and the method can not be applied.

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STUDY OF STRUCTURE OF SUWA BASIN NEAR KYOTO, JAPAN, BY TORSION BALANCE[1]

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ABSTRACT

The origin of the Suwa Basin near Kyoto, Japan, was sought from the geophysical standpoint by use of the torsion balance. An isogam map suggests Lake Suwa as a crater lake, but this conclusion is not reasonable from a geological standpoint. Therefore, the origin of the lake seems to be in subsidence following the eruption of Yatsugadake Mountain, near by.

The gravity field of the basin is negative while that of the mountains which surround the basin is positive. Hence, from the standpoint of isostasy, the deficiency of the subterranean mass is clear, and shows that the basin is a result of faulting or subsidence.

PURPOSE OF RESEARCH

From the geological standpoint, the origin of the Suwa Basin has been studied and the results of the study have been published and discussed by geologists. To examine the opinion of the geologists, this research was carried out from the geophysical standpoint so as to determine the reasons for the occurrence of the Suwa Basin and the geological history of Lake Suwa.

FIELD WORK

The field work was performed in April, 1927, and again in May and June, 1928. The Eötvös original type torsion balance was used on these two occasions. The number of observation points was 13 in the field work of 1927, and 32 in the field work of 1928, making a total of 45 stations.

COMPUTATION OF RESULTS

The topographic (including terrane, topographic, and cartographic corrections) and normal corrections were applied to the observed values. There are a number of formulas for the computation of the topographic correction, but none of them is absolute. The cor-

[1] Manuscript received, November 13, 1934.

[2] Kyoto Imperial University.

rection formula derived by C. A. Heiland[3] seems to be the most reasonable at present, and was used for the correction.

The results of density determination on a large number of samples of rocks and soils are shown in Table I.

TABLE I

DENSITY OF ROCKS AND SOILS

Names of Rocks	*Specific Gravity*	*Samples are Taken from*
Contact metamorphosed (rock)	3.05	
Andesite	2.75	
Granite	2.72	
Diabase	2.70	
Conglomerate	2.66	
Diabasic tuff	2.65	
Gabbro?	2.64	
Tuff	2.44	
Andesite	2.43	Kosaka Pass
Mean	2.71	
Soil	1.71	Road
Soil	1.52	House lot or garden
Soil	1.48	Field
Mean	1.53	

The densities of rocks surrounding the Suwa Basin differ, but from the nature of rock distribution, it was confirmed that by taking the mean density of 2.71, an error of more than 5 per cent would not arise. Hence, the density of soil was taken as 1.53 and that of rock was taken as 2.71 in the computation.

The topographic corrections were made in three stages as shown in Table II.

TABLE II

AREA OF TOPOGRAPHIC CORRECTION

Stage	*Radius in Meters with Observation Station as Center; Corrected Area*	*Maps Used for Drawing Profiles*
1	40	Surveyed by plane table
2	5,000	Topographic map Scale: 1/50,000
3	20,000	Topographic map Scale: 1/200,000

The corrected value from the three stages (Table II) was maximum in the second stage and was minimum in the first stage, due to the attention given in selecting the stations. The normal correction is the correction for the longitude of the station and has nothing to do with the latitude. The difference in longitudes between the extreme northern and southern observation stations was only 5.6 minutes.

[3] C. A. Heiland, "A New Graphical Method for Torsion Balance-Topographic Corrections and Interpretations," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. 13, No. 1 (January, 1929), pp. 39–74.

Hence the results obtained by taking the average value of 36° 20′ and calculating the influence of it was as follows:

$$B - A = \frac{\partial^2 U}{\partial y^2} - \frac{\partial^2 U}{\partial x^2} = +6.8 \qquad H = \frac{\partial^2 U}{\partial x \partial y} = 0$$

$$G = \frac{\partial^2 u}{\partial x \partial z} = +7.8 \qquad F = \frac{\partial^2 u}{\partial y \partial z} = 0$$

The results of correcting the observed values by the foregoing are shown in Figure 1.

FIG. 1.—Diagram showing gravity gradients and curvature values at Suwa Basin. (To conform to American practice in plotting, *R*-lines should be rotated through 90°.)

The determination of gravity by means of a pendulum at Kami-Suwa, conducted by the Bureau of Geodesy of Japan, gave the value of 979.629 dynes. Therefore, by taking this value as zero, the isogam lines calculated gave the results shown in Figure 2.

VARIATION OF GRAVITY FIELD

In looking at Figure 1, it is seen that the gradients point radially away from Lake Suwa, but a close examination reveals that the gradients increase in value northeast and southwest from the major axis of the Suwa Basin; near the margin of the basin they have their

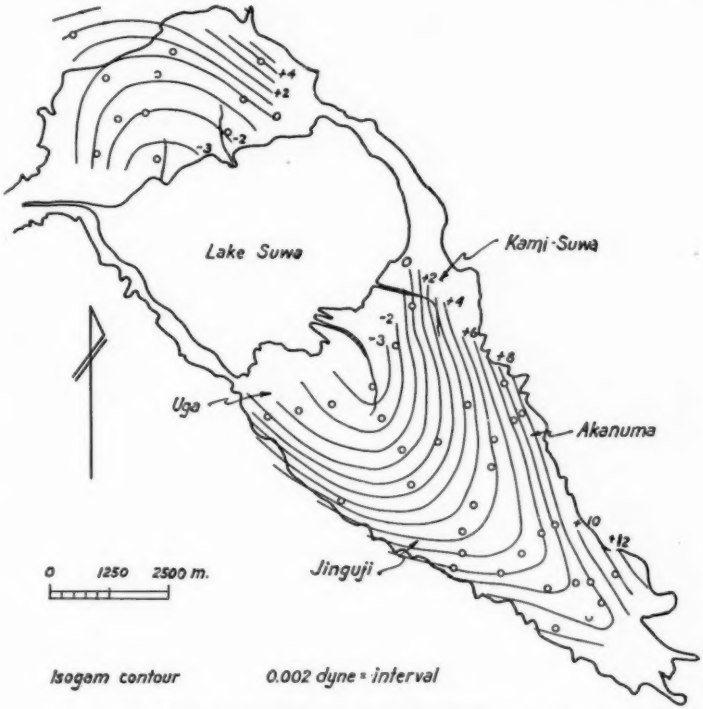

FIG. 2.—Isogam contours in Suwa Basin. (Igneous and metamorphic rocks surround Suwa Basin.)

maximum value. Along the major axis, the direction of the gradients is northwest on the northern side and southwest on the southern side of the lake. The curvature value is maximum at the center of the basin and decreases as the distance from the center increases. Furthermore, the direction of maximum curvature is parallel with the major axis at the center of the basin and is nearly perpendicular at the foot of the mountain.

DEPTH OF BED ROCK

Gradients were calculated on the assumption that a fault, the throw of which was large, is present along the east side of the margin of the basin. The variation in the observed gradients was found to be far too small. Therefore, the assumption was incorrect.

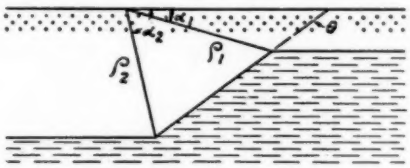

FIG. 3.—Assumed structure in Suwa Basin.

From the topography and the distribution of the corrected values of gradient and curvature, it seemed that the subterranean structure extends in the direction of the major axis of the basin. An assumed cross section is shown in Figure 3. By comparing the anomaly that arises from this assumed structure, which was computed from the following formula, the corrected observation values are obtained and the results are shown in Table III.

$$g\left(\frac{1}{R_1}-\frac{1}{R_2}\right) = -2G\sigma\left\{\sin\theta\cos\theta\log\frac{\rho_2}{\rho_1}+\sin^2\theta(\alpha_2-\alpha_1)\right\}$$

$$\frac{\partial g}{\partial s} = +2G\sigma\left\{\sin^2\theta\log\frac{\rho_2}{\rho_1}-\sin\theta\cos\theta(\alpha_2-\alpha_1)\right\}$$

TABLE III

GRAVITY ANOMALIES DUE TO STRUCTURE SHOWN IN FIGURE 3

Place	*No. of Sta.*	*Assumed Inclination*	*Value Depth (Meters)*	*Horizontal Distance (Meters)*	*Observed Value*	*Calculated Value*
	11			275	132.4	108.5
Akanuma	15	12°44′	313	447	92.0	101.2
	16			1,010	77.6	76.5
	17			1,327	36.0	46.7
	21			192	102.0	103.1
Jingugi	20	12°44′	173	568	50.4	72.5
	19			983	27.8	12.3
	6			308	123.2	109.0
Uga	4	12°34′	450	900	94.0	94.1
	5			1,519	51.0	73.9

In the vicinity of observation station No. 14 the presence of an active fault is being considered because of the subsidence of the railroad track and because of the geological features. If the active fault is slipping westward, an explanation of the discrepancy between the calculated and the corrected observation values can be made.

If the depth and the dip of the bed rock are assumed, as shown in Figure 3, the calculated results satisfactorily coincide with the observed values. The depth of the bed rock increases as the center of the lake is approached.

CONCLUSION

The maximum computed depth to bed rock is 450 meters; therefore, the basin can not be considered as formed by weathering only, when located in Japan. Its origin should be considered as from sinking or from volcanic eruption.

The isogams of Figure II lead us to believe that Lake Suwa is a crater lake. This theory is rejected, however, as unreasonable from the geologic standpoint. Therefore, the origin of the lake should be regarded as due to a sinking or subsidence following the eruption of the Yatsugadake Mountain, near by. If the origin is sinking, the occurrence of a fault at the margin of the basin is a matter of course. The volcanic lava and debris from the Yatsugadake Mountain were carried down into the sunken zone and deposited in the basin, forming an alluvial fan. The thickness of the deposition is much greater on the southern side than on the northern side of the lake.

The gravity field of the basin is negative, while that of the mountains which surround the basin is positive. Hence, from the standpoint of isostasy, the deficit of the subterranean mass is clear, and shows that the basin is a result of faulting or subsidence.

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DEEP ELECTRICAL PROSPECTING[1]

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ABSTRACT

By deep electrical prospecting is meant depths of a half mile or more. Most data so far published refer to depths appreciably shallower than this. A continuous current field is most satisfactory together with electrode spacing comparable with the depth of the insulating media. Electrical prospecting is here regarded in the light of its ability to determine the presence of insulating rather than conducting media. Use is made of resistivity determinations at various electrode spacings together with inductance and resistivity slope functions. Inductance is determined by measuring the time constant of the current decay. Three areas are considered. One, the Hugoton gas area, Stevens County, Kansas, is an ideal case for the electrical method. In the other two cases considered, the Hebbronville area, Jim Hogg County, Texas, and the Anderson County, Kansas, area, the electrical method is quite ineffectual.

Most of the published data on the electrical method of geophysical prospecting have been for rather short electrode spreads and consequently afforded information for relatively shallow depths. A further limitation as regards depth has been the use of an alternating current source to establish a field in the earth. In the following examples a continuous current was employed and interrupted at regular intervals of about 10 seconds. With the longer electrode spacings time constants of the order of one-tenth second were not unusual. It is therefore obvious that for deep penetration it is undesirable to employ alternating current of frequencies higher than a few cycles per second. In view of the difficulty of obtaining large currents of such low frequency, the advantages of a continuous current are apparent.

A current spread of one-half mile (distance between current electrodes) was used throughout. A pair of potential electrodes was placed at varying distances in line with the current electrodes and outside the current electrodes, as indicated in Figure 1. The distance from the inside current electrode to the inside potential electrode is the distance between current and potential electrodes referred to in what follows. The separation of potential electrodes was made as large as necessary to obtain a satisfactory value of voltage. This

[1] Read before the Geophysics Division of the Association at the Dallas meeting, March 23, 1934. Manuscript received, December 4, 1934.

[2] Geophysical Service, Inc., Republic Bank Building.

voltage was amplified by means of a calibrated D.C. amplifier and applied to a galvanometer, the motion of which was photographed. This gave a permanent record and permitted the determination of the voltage and time constant. The disposition of electrodes is designated by the current electrode separation, the distance between the nearest current and potential electrodes, and the potential electrode spacing. For instance, an electrode disposition represented by .5–.4–500′ means that the current electrode separation is one-half mile, the distance between the nearest current and potential electrodes is four-tenths mile and the potential electrode separation is 500 feet. A storage battery of several hundred volts employed as a source delivered 10–20

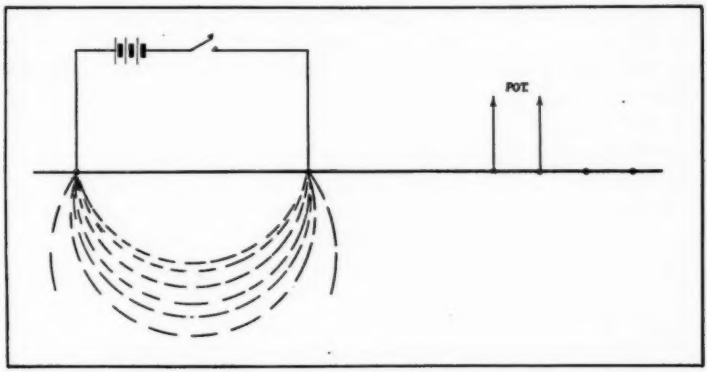

FIG. 1.—Disposition of electrodes.

amperes to the current electrodes which were a multiplicity of copper rods. The usual non-polarizing potential pots were used for the potential electrodes.

Electrical prospecting is here regarded in the light of its ability to determine the presence of insulating rather than conducting media. It would seem that if the electrical method is to be of any considerable value to the petroleum geologist it must prove itself of value in this respect. As rocks filled with oil and gas exhibit much higher resistivities than when filled with mineralized water in the usual case, this would seem the most logical and desirable use of the electrical method. It is well known that the resistivity of dry rock is very high. The comparatively low resistivities observed in electrical prospecting are due to the mineralized water in the rock pores acting as an electrolyte. It is apparent, therefore, that when the pore space is small or when this

space is filled with fresh water, gas, or oil, the apparent resistivity of the rock as observed by the ordinary methods of electrical prospecting will be large. Non-porous limestone, therefore, and porous sands where the mineral content of the water is small will indicate high resistivity. This, together with the fact that the areal extent of oil- or gas-filled media is in general small compared with the depth of such media below the surface, suggests at the outset that there are real limitations to the use of the electrical method as far as its use for the direct detection of reasonably deep oil- and gas-saturated media is concerned. Likewise the use of the electrical method for exploring the subsurface structurally at any depth likely to be of value will find its limitations in the lateral variation of resistivity due to changing porosity of the various media and mineral content of subsurface waters, the first mentioned probably offering the greater obstacle. Granite, due to its small porosity, exhibits a very high resistivity. It should, therefore, be possible to determine subsurface structure in the granite provided the lateral extent of the uplift and the amount of relief are sufficiently large in comparison with the depth of the surface of the granite.

If it is assumed that the electrical method is to be used to discover the presence of electrically resistant media, such as oil and gas sands, it is safe to generalize to the extent of saying that to determine the presence of such media with a reasonable degree of certainty *the smallest lateral dimension of the high-resistance medium must be at least several times the depth of the medium below the surface.* The Hugoton gas field in Stevens County, Kansas, as here demonstrated, definitely comes under this category. Without much doubt the East Texas field also should be included, although this is now impossible to determine due to the large number of cased wells in the field. The electrical method is of no value if cased wells are in the vicinity of any of the electrodes.

The resistivity was determined from the following relation:

$$\Delta V = \frac{I\rho A}{\pi(x_1^2 - A^2)} - \frac{I\rho A}{\pi(X_2^2 - A^2)}$$

$$\rho = \frac{\pi \Delta V}{IA} \times \frac{1}{\dfrac{1}{X_1^2 - A^2} - \dfrac{1}{X_2^2 - A^2}}$$

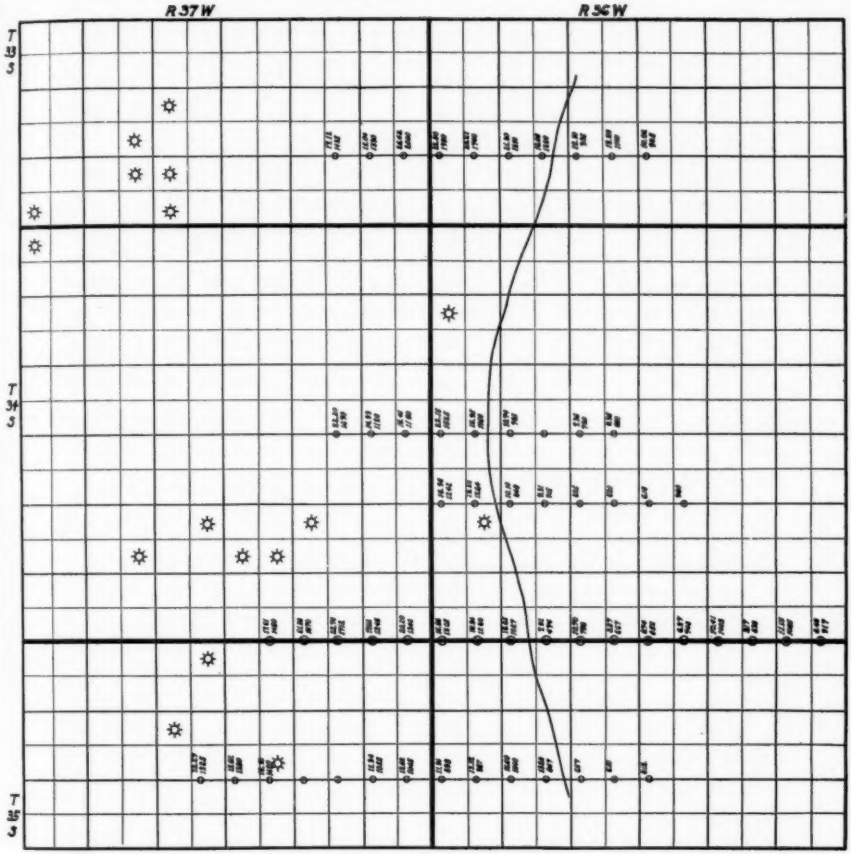

FIG. 2.—Hugoton gas area.

where ΔV is the potential difference between potential electrodes in volts, I is the current flowing from the current electrodes in amperes, ρ is the resistivity in ohms per centimeter cube, A is the half current spread in centimeters, X_1 and X_2 are the distances from the center of the current spread to the potential electrodes. It is obvious that if the medium is homogeneous the value of ρ will be independent of the position of the potential electrodes (X_1 and X_2). As the ground is nonhomogeneous the value of ρ will depend on the position of the potential electrodes. The variations from normal as the potential electrodes are moved permits an approximation of subsurface resistivities.

As the current does not reach its maximum immediately upon application of a voltage on the current electrodes, or does not immediately return to zero on removal of the voltage, the path of the current through the ground has an effective inductance. The current rises and decays logarithmically in point of time, exactly the characteristic of an electrical circuit comprising an inductance and resistance in series. Now L/R is the time constant of the circuit and represents the time required for the current to decay to $1/\epsilon$ of its initial value. This may easily be measured from the photographic record of the voltage and R may be approximated from the resistivity measurements. Thus we arrive at a quantity which is a functoin of the inductance and is here designated the inductance function.

Although the shorter spreads are affected principally by the near-surface conditions, an abnormal surface resistance will have some residual effect on the longer spreads. A quantity, therefore, which is a function of the resistivity as determined by the longer spread and the slope of the resistivity profile will further eliminate the near-surface effects. This we will call the resistivity-slope function. The slope is measured by the angle the resistivity profile makes with the vertical and increases in a clockwise direction.

Electrical surveys of three areas are here described. In one area the Hugoton gas field, resistivities, inductance and resistivity-slope functions are all determined and compared. In the other two areas, the Hebbronville area in Jim Hogg County, Texas, and the Anderson County area in Kansas, only the resistivities are used. J. V. Polk, of Geophysical Service, Inc., deserves credit for the field work, most of which was conducted under his direction during 1932.

HUGOTON GAS AREA

The Hugoton gas field is one of the largest gas fields known, covering the western part of Stevens County, Kansas, and extending into several adjacent counties. The gas sand, the thickness of which is not

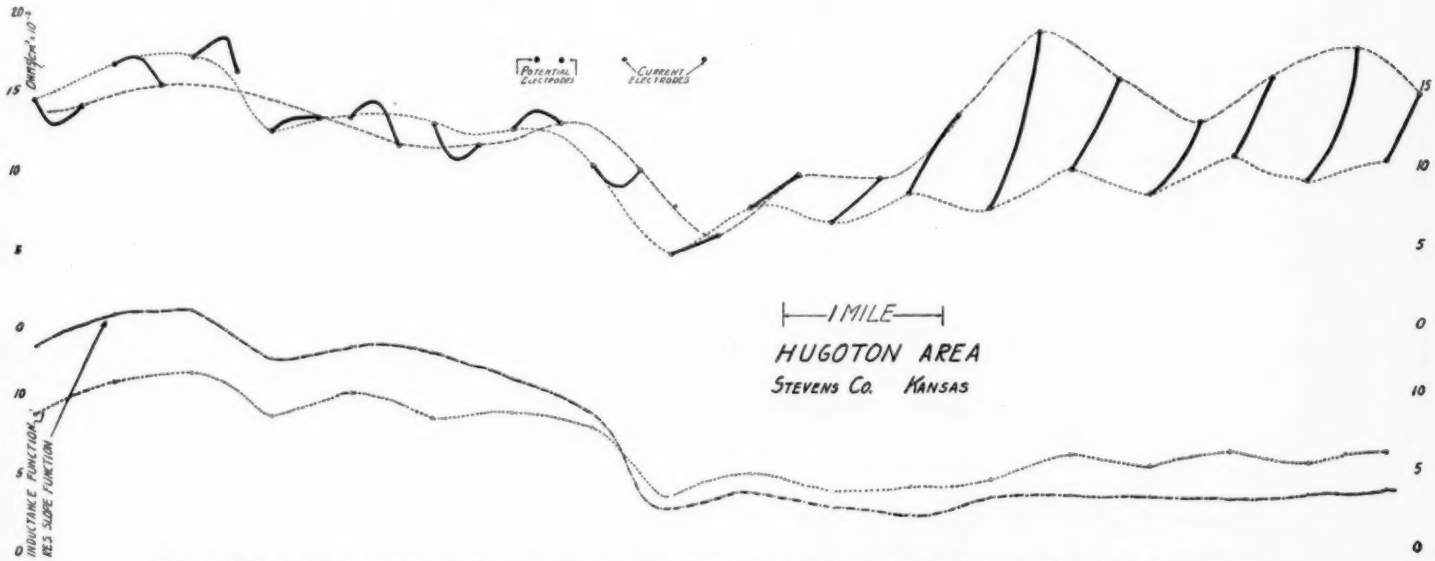

FIG. 3.—Electrical profile across east edge of Hugoton gas area, showing values of resistivity, also inductance function for longest spread.

accurately known, lies at a depth somewhat greater than one-half mile below the surface. A number of lines of electrical profiles were run in east and west directions, traversing the east edge of the field. This particular portion of the field is shown in Figure 2, together with the resistivity values and the inductance function values for the longest electrode spread on each profile. A profile consists of four potential electrode positions, namely, .4, .5, .6, and .7 mile from the inside potential electrode to the inside current electrode. The separation of the two potential electrodes ranged from 500 feet to 1,000 feet, the minimum value necessary to secure a good record being chosen in each case. This choice is not critical. The distance between current electrodes was .5 mile. These, according to a previous statement of nomenclature, are designated as:

.5–.4– 500′
.5–.5– 500′
.5–.6–1,000′
.5–.7–1,000′

The north-south trending line through R. 36 W. indicates the electrically determined east edge of the gas field.

In the upper portion of Figure 3 are shown the resistivity determinations for the line of profiles indicated in Figure 2 along the township line. Although only the two end values are indicated on the profiles, the profiles were determined from the four values specified above. The profiles run from right to left, the shorter electrode spacing being on the right. The relative disposition of the electrodes is indicated for one profile.

Attention is called to the fact that resistivity values for the .5–.4–500′ set-up are on the average equally high, while some are even higher, east of the gas field than over the gas sand. On the other hand, the .5–.7–1,000′ resistivity values are on the average decidedly higher over the gas sand than outside the bounds of the field. As a result of this, the shape of the profile curve is markedly different in the two cases. One of the curves in the lower portion of the figure represents the inductance function. This follows the same general pattern as that of the .5–.7–1,000′ resistivity line above, but the change across the field border is of greater magnitude. In this particular case all indices, the longer spread resistivities, inductance function and resistivity-slope function clearly indicate the presence of the insulating gas sand with a remarkable degree of certainty. This field amply satisfied the condition postulated, namely that the minimum dimensions of the insulating layer should be at least several times the depth. It is evident also that, in such a case as this, further manipulation of the data

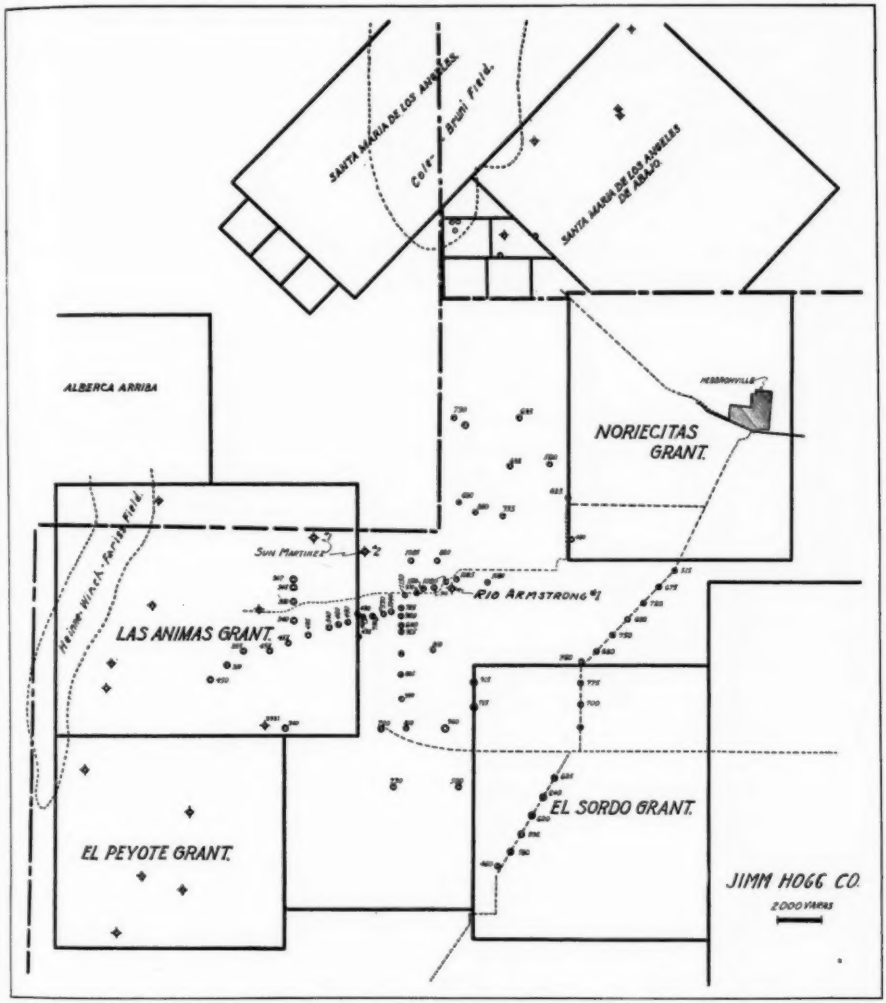

FIG. 4.—Hebbronville area.

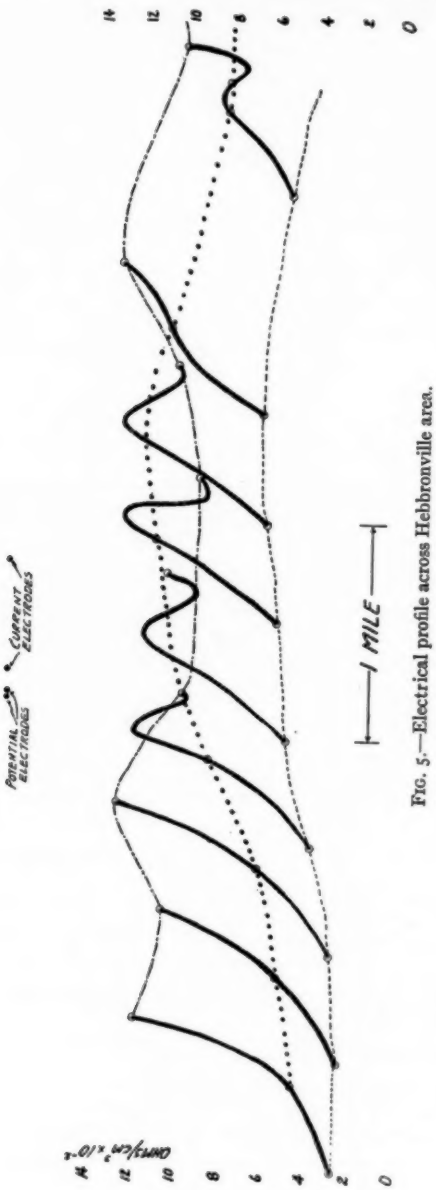

FIG. 5.—Electrical profile across Hebbronville area.

beyond the original resistivity determination adds but little to the value of the data. It would seem therefore that the limitations of the electrical method are apt to be more fundamental than the choice of instrument design or electrode arrangement. The following two cases support this view.

HEBBRONVILLE AREA

The center of the area surveyed lies about 10 miles southwest of the town of Hebbronville in Jim Hogg County, Texas. The electrical work in this area was completed previous to the drilling of any wells. The resistivity measurements were made in a manner similar to that in the foregoing illustrations. The location of resistivity points is indicated in Figure 4. The effective resistivity point is assumed to be half way between the inside potential electrode and the inside current electrode. The potential electrodes were placed at distances of .1, .2, .3, .4, .6, and .8 mile from the nearest current electrode. For the sake of clarity, not all of these positions are indicated in Figure 5, which represents a line of profiles east and west across the center of the area, east being at the right. The Rio Oil Corporation Armstrong No. 1 was drilled slightly east of the center of the profile. The broken connecting lines shown join corresponding points on the different profiles, namely, the .1, .4, and .8 mile potential-electrode points. The .1 mile point indicates a resistivity syncline where the .4 and .8 mile potential points evidence a resistance anticline, that is, high-resistance values. The .2 potential point not shown also demonstrates a resistivity syncline. It is therefore evident that the resistivity "high" indicated by the longer spreads is not the reflection of a surface condition but must be attributed to a subsurface effect at a depth of the order of the electrode separation, namely, .4 mile. This is assumed to be the case because the short electrode separations are affected oppositely and the longest separation, namely .8 mile, indicates a smaller resistivity "high" than the .4 mile position. This is the effect expected in the case of a poor insulator. The contour maps of Figure 6 are the result of contouring all resistivity values in the one case for the .5–.4–500′ set-up and in the other for the .5–.8–1,000′ set-up.

The Rio Oil Corporation well was drilled at the center of the "high" as shown in Figure 6. This well had no showing of gas or oil and upon correlation with the two Sun Oil Company Martinez wells later drilled at the west, was found to be structurally much lower than either. The following datum values on the Vicksburg were kindly furnished by the Sun Oil Company.

Sun Oil Company	Martinez No. 1	− 710
Sun Oil Company	Martinez No. 2	− 930
Rio Oil Corporation	Armstrong No. 1	−1390

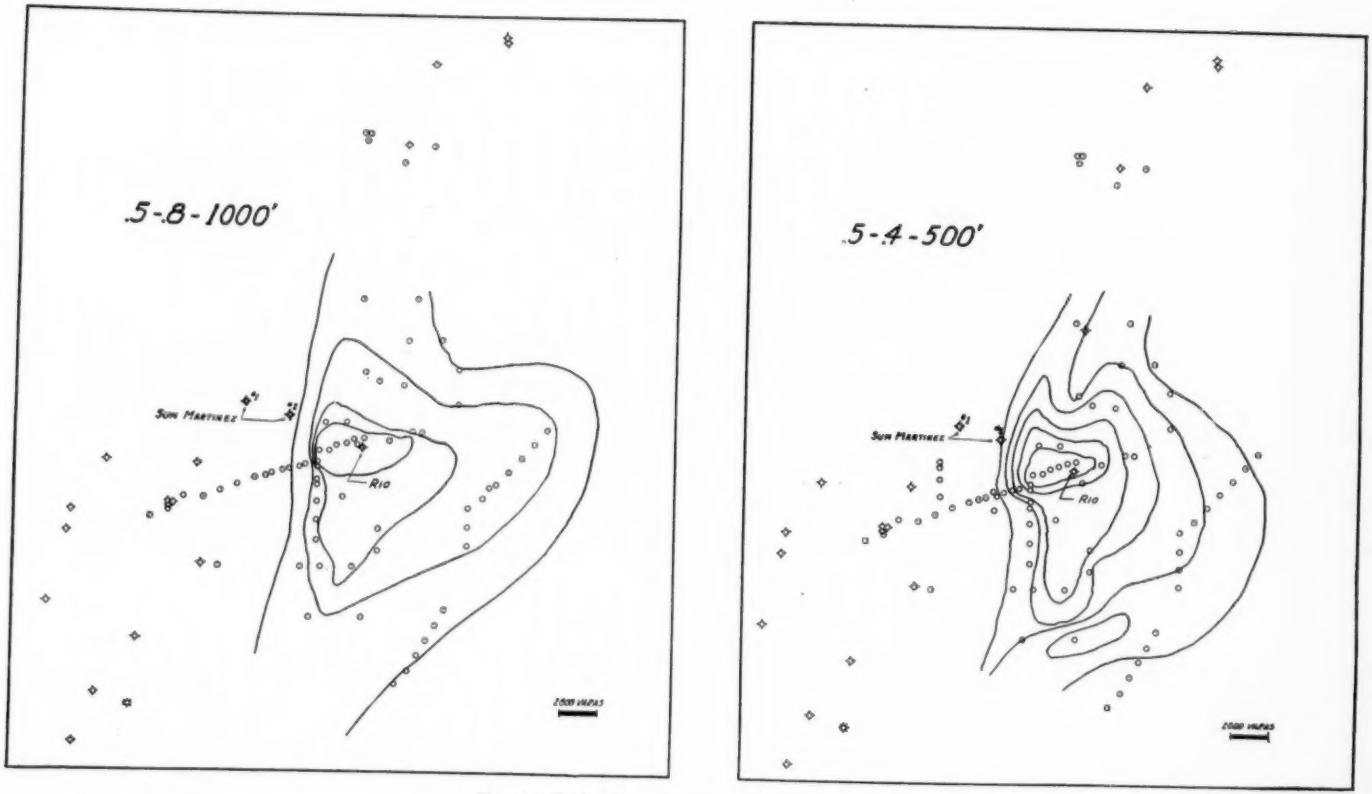

FIG. 6.—Resistivity contours, Hebbronville area.

Obviously there is no agreement whatever between the electrical and well data, either as regards the presence of an oil or gas sand or the structural condition. Therefore, it must be concluded that the resistivity "high" was caused by a lateral change in porosity or mineral content of subsurface water at a depth of approximately .4 mile. It was reported that the well made considerable fresh water between

TABLE I

RIO OIL CORPORATION'S E. L. ARMSTRONG NO. 1

JIM HOGG COUNTY, TEXAS

Formation	*Depth in Feet*
Caliche	20
Sand and caliche	100
Sand	125
Hard shale	150
Gravel	160
Hard shale	200
Sand	205
Shale	275
Sand and gravel	290
Hard shale	380
Hard sand	402
Hard cemented gravel	442
Hard sand gravel	505
Hard cemented gravel	597
Hard sand gravel	652
Hard sand	662
Hard gravel	682
Hard shale	700
Hard sand gravel	732
Shale	1051
Sticky shale	1325
Sandy shale	1425
Shale	1576
Sticky shale	1650
Shale	1700
Sticky shale	1776
Sandy shale (cored)	1781
Shale	1941
Sticky shale (cored 1,935–55)	1975
Sticky shale	2016
Shale (cored 2,016–36)	2110
Sticky shale	2186
Sand (cored)	2223
Hard sand	2240
Shale	2269
Hard sand (cored 2,270–75)	2275
Sand	2290
Broken sand	2320
Shale	2369
Hard sand rock (cored, 2,369–71)	2375
Sand (cored)	2382
Hard sand rock	2384
Hard sand	2435
Hard sand rock	4440
Shale	2460
Shale and lime (cored)	2468
Shale	2505

FIG. 6.—Resistivity contours, Hebbronville area.

1,600 and 2,000 feet. If so, this fact may well account for the resistivity "high" observed. This case illustrates very well some of the limitations of the electrical method as previously discussed. A driller's log of the well is given in Table I.

ANDERSON COUNTY, KANSAS, AREA

The area under consideration is located in Sec. 10, T. 23 S., R. 20 E., Anderson County, Kansas. The procedure was exactly the same as followed in the two foregoing cases. The following spreads were employed: .5–.1–10′, .5–.2–20′, .5–.3–150′, and .5–.4–500′. The contour maps shown in Figure 8 for the four different spreads suggest the presence of an insulator at a depth of somewhat less than 500 feet. As the spread is increased, the effect of this disappears as shown

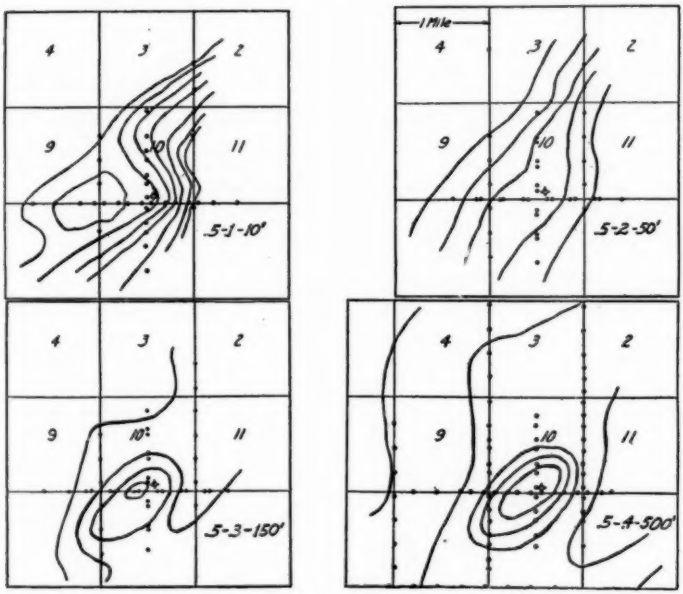

FIG. 7.—Resistivity contours, Anderson County, Kansas, area.

on the contour map for the .5–.2–50′ set-up. Upon further lengthening the spread, the presence of another insulator is indicated. A well drilled on the south side of Section 10, with the exception of a very slight showing of gas at 550 feet, was abandoned at a total depth of

1,056 feet as a dry hole. The log of this well (Table II) shows considerable limestone. The only conclusion that may be drawn is that

TABLE II

WREN WELL NO. 1, SEC. 10, T. 23 S., R. 20 E.,
ANDERSON COUNTY, KANSAS

Formation	*Depth in Feet*
Shale	10
Lime	12
Shale	115
Lime	150
Blue shale	185
Lime	188
Shale, dark	216
Lime	220
Shale	225
Lime	256
Shale	258
Lime	281
Dark shale	286
Lime	306
Shale	311
Lime	335
Shale	510
Lime	512
Shale	525
Lime	531
Shale	602
Lime	617
Blue shale	637
Lime	652
Blue shale	663
Lime	678
Blue shale	686
Lime	692
Shale	765
Lime	768
Dark shale	788
Lime	790
Blue shale	805
Light shale	815
Dark shale	837
Light shale	840
Dark shale	930
Sand	941
Blue shale	967
Sand	982
Broken sand	990
Dark shale	1049
Broken lime	1054
Lime	1056

this case falls into the same category as the preceding one of the Hebbronville area.

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NORMAL GEOTHERMAL GRADIENT IN UNITED STATES[1]

C. E. VAN ORSTRAND[2]
Washington, D.C.

ABSTRACT

The objects in preparing this paper have been, first, to prepare a brief summary of the gradients deduced from recent geothermal surveys in the United States; and second, to discuss the data thus summarized from the standpoint of a normal geothermal gradient.

INTRODUCTION

In 1920, N. H. Darton (1)[3] published a summary of geothermal data in the United States. With but few exceptions, the data for the individual states consisted of temperatures recorded in flowing wells. Since the appearance of Darton's publication, the United States Geological Survey and the American Petroleum Institute (2) have added to the list the records of about 700 non-flowing wells located chiefly in the oil-producing states. These observations, including Darton's records, have never been discussed from the standpoint of a normal geothermal gradient; but, in view of the constant use of the term in geological literature, it is necessary that the term be properly defined and that the limitations of the definition be determined, as nearly as possible, from existing data.

HORIZONTAL AND VERTICAL VARIATION OF GRADIENTS

Recent geothermal surveys have shown without question that geothermal gradients vary uniformly in both the horizontal and the vertical. Any attempt, therefore, to approximate to a normal gradient must take these two important variations into account.

Variation in the horizontal is illustrated by reference to Figure 1, which represents the cross section of a typical oil field anticline. Observations show that in a majority of cases the isogeotherms ($a''a'a$,

[1] Published with the permission of the director, United States Geological Survey.

[2] Geophysicist, United States Geological Survey. Manuscript received, June 28, 1934. To the writer's assistant, H. Cecil Spicer, special credit is due for very valuable and efficient service rendered in carrying out the extensive calculations involved in the preparation of this and other recent papers on geothermal gradients.

[3] This and the following references are in the bibliography at the end of this article.

$c''c'c$) rise in passing over the anticlines. Expressed in terms of gradients, this is the equivalent of saying that the gradients are a maximum, or the reciprocal gradients are a minimum, along the crests of the anticlines.

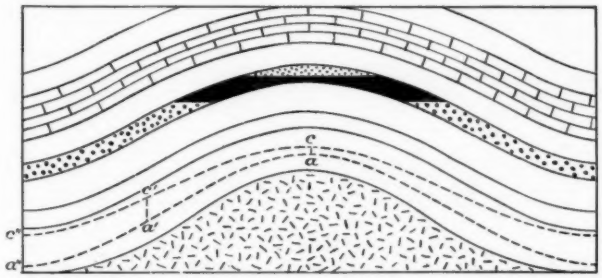

FIG. 1.—Cross section of typical anticline.

Variations in the vertical are illustrated by the concave and convex types of depth-temperature curves (AA' and BB') shown in Figure 2. Each of the lines *cc* and *ee* represents the least square adjustment of a straight line through all of the observed points from

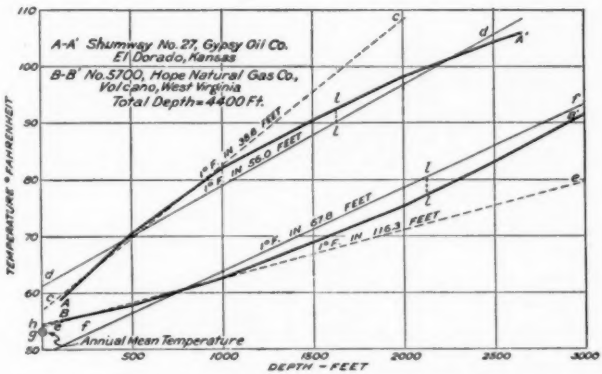

FIG. 2.—Concave and convex types of depth-temperature curves.

100 to 1,000 feet inclusive on the respective curves. Similarly, the lines *dd* and *ff* were obtained by adjusting, in each case, a straight line through all of the points from 100 feet to the greatest depth, inclusive, at which a reading was taken. In curves of the concave

TABLE I

TEMPERATURE GRADIENTS. ISOLATED LOCATIONS AND FLANKS OF STRUCTURES

Town	State	No. of Wells	$b \times 10^6$. Degrees F. per Foot				Total Depth Feet	$b \times 10^6$ 100-Total Depth	1/b 100-Total Depth Ft. °F.	$b \times 10^6$ 0-Total Depth
			100-1,000 Feet	100-2,000 Feet	100-3,000 Feet	100-4,000 Feet				
Albany	Alabama	1	259	398	—	—	2,000	398	251.1	355
Birmingham	Alabama	7	914	955	—	—	2,000	955	104.7	750
Fayette	Alabama	1	780	—	—	—	1,250	832	120.1	632
El Dorado	Arkansas	7	1,862	2,329	—	—	2,000	2,329	42.9	2,240
Bakersfield	California	5	1,198	1,236	1,338	1,464	4,250	1,569	63.7	1,911
Coalinga	California	51	1,413	—	—	—	1,370	1,351	74.0	1,956
Fullerton	California	1	2,009	2,070	1,983	1,932	4,270	1,919	52.1	2,133
Grass Valley	California	1	593	569	537	—	3,400	527	189.8	497
Huntington Beach	California	4	2,225	2,456	2,624	—	3,500	2,643	37.8	2,786
Kettleman Hills	California	4	1,612	—	—	—	1,350	1,671	59.9	2,244
Long Beach	California	40	1,607	1,681	—	—	2,500	1,642	60.9	2,204
Santa Fe Springs	California	31	1,535	1,819	1,895	—	4,250	1,904	52.5	1,995
Seal Beach	California	1	2,949	2,398	2,277	—	3,500	2,256	44.3	2,346
Whittier	California	4	1,670	1,809	1,885	—	3,750	1,874	53.4	2,136
Calhan	Colorado	1	1,575	1,570	1,610	1,712	4,000	1,712	58.4	1,863
Florence	Colorado	3	1,532	1,848	—	—	2,900	2,020	49.5	2,090
Fort Collins	Colorado	2	1,667	1,755	1,858	1,956	4,000	1,956	51.1	2,050
Longmont	Colorado	1	1,775	2,018	2,152	2,251	6,500	2,399	41.7	2,489
Bridgeport	Illinois	4	1,456	—	—	—	1,250	1,526	65.5	1,704
Ames	Iowa	1	695	731	—	—	2,100	710	140.9	686
Augusta	Kansas	2	1,945	2,009	—	—	2,250	1,984	50.4	2,013
El Dorado	Kansas	24	1,777	1,827	—	—	2,250	1,799	55.6	1,689
Florence	Kansas	4	1,361	—	—	—	1,750	1,590	62.9	1,686
Haverhill	Kansas	3	1,720	1,819	—	—	2,750	1,783	56.1	1,811
Syracuse	Kansas	1	1,219	1,277	1,338	—	4,600	1,428	70.0	1,485

TABLE I (*Continued*)

Town	State	No. of Wells	$b \times 10^5$. Degrees F. per Foot				Total Depth Feet	$b \times 10^5$ 100–Total Depth	1/b 100–Total Depth Ft. °F.	$b \times 10^5$ 0–Total Depth
			100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet				
Prater Creek	Kentucky	1	820	—	—	—	1,500	637	157.0	620
Rockcastle Creek	Kentucky	1	844	—	—	—	1,500	764	130.9	600
Blue Lake	Louisiana	2	1,786	—	—	—	1,500	1,993	50.2	2,180
Caddo Lake	Louisiana	1	2,653	2,423	—	—	2,000	2,423	41.3	2,325
Caddo Lake (near)	Louisiana	3	2,674	2,413	—	—	2,250	2,391	41.8	2,333
Haynesville	Louisiana	1	2,075	2,273	—	—	2,750	2,245	44.5	2,160
Homer	Louisiana	8	2,518	—	—	—	1,150	2,646	37.8	2,357
Many	Louisiana	6	1,883	—	—	—	1,250	1,926	51.9	1,832
Pine Island	Louisiana	1	2,845	2,451	2,269	—	3,500	2,218	45.1	2,234
Sligo	Louisiana	2	2,588	—	—	—	1,650	2,318	43.1	2,218
Zwolle	Louisiana	3	1,751	—	—	—	1,250	1,771	56.5	1,792
Houghton	Michigan	4	771	—	—	—	6,250	922	108.4	845
Lake Linden	Michigan	1	624	—	—	—	1,435	757	132.2	983
Surrey Twp.	Michigan	1	1,186	1,378	1,748	—	3,700	1,887	53.0	1,754
Jackson	Mississippi	1	2,906	2,861	—	—	2,250	2,832	35.3	2,676
Anaconda	Montana	1	2,635	—	—	—	1,600	2,111	47.4	1,969
Kevin-Sunburst	Montana	10	930	978	987	—	3,000	987	101.4	1,123
Virginia City	Nevada	1	3,396	3,129	—	—	2,300	3,105	32.2	3,061
Franklin-Furnace	New Jersey	1	362	—	—	—	2,500	585	170.8	640
Artesia	New Mexico	3	560	478	—	—	2,892	439	227.7	598
Carlsbad	New Mexico	1	680	583	—	—	2,874	578	173.1	703
Lovington	New Mexico	1	1,252	941	733	594	4,500	554	180.5	640
Roswell	New Mexico	2	439	540	576	—	2,950	576	173.5	773
Lonetree	North Dakota	1	1,578	1,654	1,806	—	3,750	1,998	50.0	2,157
Ardmore	Oklahoma	4	657	—	—	—	1,500	678	147.5	667

TABLE I (*Continued*)

Town	State	No. of Wells	$b \times 10^5$. Degrees F. per Foot				Total Depth Feet	$b \times 10^5$ 100–Total Depth	$1/b$ 100–Total Depth Ft.°F.	$b \times 10^5$ 0–Total Depth
			100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–3,000 Feet				
Ardmore-Healdton	Oklahoma	9	616	—	—	—	1,500	657	152.2	593
Ardmore-Hewett	Oklahoma	8	808	—	—	—	1,750	950	105.3	800
Bessie	Oklahoma	1	707	—	—	—	1,500	828	120.7	920
Billings	Oklahoma	1	1,891	1,910	1,895	—	3,500	1,911	52.3	1,937
Blackwell	Oklahoma	2	2,038	2,027	—	—	2,000	2,027	49.3	1,900
Braman	Oklahoma	3	1,758	—	—	—	1,410	1,829	54.7	1,787
Burbank	Oklahoma	3	1,893	2,093	—	—	2,850	2,188	45.7	2,172
Covington	Oklahoma	1	—	—	—	—	1,600	1,933	51.7	1,919
Cromwell	Oklahoma	9	1,886	—	—	—	1,200	1,918	52.1	1,775
Davenport	Oklahoma	1	882	988	1,101	—	3,375	1,162	86.0	1,132
Dilworth	Oklahoma	11	1,743	1,848	1,874	—	3,000	1,874	53.4	1,953
Drumright	Oklahoma	28	880	1,381	—	—	2,210	1,467	68.2	1,416
Glenn Pool	Oklahoma	18	2,284	—	—	—	1,500	2,383	42.0	2,187
Holdenville	Oklahoma	1	—	—	1,891	1,925	5,200	2,002	49.9	1,996
Hubbard	Oklahoma	1	2,066	2,054	—	—	2,870	2,103	47.6	2,136
Morris	Oklahoma	1	2,551	—	—	—	1,610	2,454	40.7	2,410
Newkirk	Oklahoma	1	2,264	2,202	2,224	—	3,000	2,224	45.0	2,270
Okemah	Oklahoma	4	2,341	2,240	—	—	2,500	2,241	44.6	2,444
Oklahoma City	Oklahoma	3	659	765	841	904	4,000	904	110.7	1,023
Papoose	Oklahoma	4	1,903	1,945	—	—	2,500	2,014	49.7	2,168
Perry	Oklahoma	1	1,820	1,677	1,717	—	3,000	1,717	58.2	1,670
Sasakwa	Oklahoma	2	1,326	1,480	—	—	2,620	1,518	65.9	1,443
Seminole	Oklahoma	19	1,019	1,314	—	—	2,750	1,340	74.6	1,284
Tonkawa	Oklahoma	15	1,569	1,831	—	—	2,750	1,840	54.3	1,876
Walters	Oklahoma	10	750	—	—	—	2,150	864	115.7	902

TABLE I (*Continued*)

Town	State	No. of Wells	$b \times 10^5$. Degrees F. per Foot				Total Depth Feet	$b \times 10^5$ 100–Total Depth	1/b 100–Total Depth Ft. °F.	$b \times 10^5$ 0–Total Depth
			100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet				
Wewoka	Oklahoma	5	1,951	2,063	2,107	—	3,000	2,107	47.5	2,087
Astoria	Oregon	1	1,503	1,615	1,656	—	3,780	1,670	59.9	1,659
Burns	Oregon	1	—	—	—	—	300	5,850*	17.1	8,100*
Klamath Falls	Oregon	2	—	—	—	—	625	4,909*	20.4	5,840*
Klamath Falls	Oregon	1	—	—	—	—	500	730	137.0	900
Medford	Oregon	2	—	—	—	—	899	1,320	75.7	1,846
Merrill	Oregon	1	—	—	—	—	660	2,471	40.5	2,924
Vale	Oregon	1	5,110*	—	—	—	1,295	4,575*	21.9	5,042*
Gaines Junction	Pennsylvania	1	1,060	1,085	1,218	1,413	5,500	1,619	61.8	1,569
Johnstown	Pennsylvania	1	919	1,121	1,171	1,157	6,500	1,313	76.2	1,358
Long Bridge	Pennsylvania	3	1,370	1,473	1,480	1,482	6,500	1,674	59.7	1,634
McDonald	Pennsylvania	1	764	903	1,045	1,190	6,975	1,444	69.2	1,325
McKeesport	Pennsylvania	1	—	—	1,249	—	3,250	1,268	78.9	1,243
Bastrop	Texas	1	2,073	2,110	—	—	2,000	2,110	47.4	2,430
Big Lake	Texas	16	672	—	—	—	1,500	636	157.3	873
Blue Ridge	Texas	7	—	1,706	—	—	2,900	1,800	55.6	1,828
Boggy Creek	Texas	3	—	2,499	2,820	—	3,703	2,867	34.9	2,768
Bonham	Texas	1	2,276	—	—	—	1,140	2,186	45.7	2,237
Callisburg	Texas	1	971	918	949	—	3,680	982	101.8	978
Canadian	Texas	1	794	806	918	939	4,758	1,001	99.9	1,051
Dale	Texas	1	2,144	2,298	—	—	2,250	2,299	43.5	2,262
Damon	Texas	1	—	1,434	1,512	1,619	4,000	1,619	61.8	1,715
Del Rio	Texas	2	1,262	1,432	1,372	—	3,686	1,311	76.3	1,373
De Witt County	Texas	1	1,753	1,902	—	—	1,970	1,902	52.6	1,949
Dickens	Texas	1	1,024	871	—	—	2,400	877	114.0	1,017

TABLE I (*Continued*)

Town	State	No. of Wells	$b\times10^5$. Degrees F. per Foot				Total Depth Feet	$b\times10^5$ 100–Total Depth	1/b 100–Total Depth Ft.°F.	$b\times10^5$ 0–Total Depth
			100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet				
Eastland	Texas	1	1,760	1,857	1,885	—	3,000	1,885	53.0	1,973
Edwards	Texas	1	1,251	—	1,267	1,365	6,600	1,666	60.0	1,691
Electra	Texas	1	1,159	—	—	—	1,830	1,224	81.7	1,213
Ennis	Texas	1	1,716	—	—	—	1,325	1,856	53.9	2,181
Ferris	Texas	1	2,034	—	—	—	1,250	2,024	49.4	2,032
Graford	Texas	1	1,736	1,734	1,856	—	3,000	1,856	53.9	1,933
Graham	Texas	2	1,502	1,630	1,638	—	3,000	1,638	61.0	1,830
Grand Saline	Texas	4	—	—	—	—	875	1,006	62.2	1,977
Greenville	Texas	1	1,952	—	—	—	1,750	1,855	53.9	1,903
Guthrie	Texas	1	1,068	841	898	—	2,950	898	111.3	1,108
Humble	Texas	28	1,458	1,677	—	—	2,000	1,677	59.6	1,560
Leonard	Texas	1	1,799	1,586	—	—	2,500	1,487	67.3	1,532
Long Point	Texas	8	1,789	1,831	1,777	—	3,300	1,765	56.7	1,794
Luling	Texas	4	1,489	1,832	—	—	2,500	1,886	53.0	2,184
Lytton Springs	Texas	7	2,464	—	—	—	1,350	2,297	43.5	2,356
Mexia	Texas	6	1,820	2,072	—	—	2,900	2,099	47.6	2,369
Muenster	Texas	1	1,360	—	—	—	1,500	1,454	68.8	1,173
Odessa	Texas	1	693	717	—	—	1,985	717	139.4	912
Ozona	Texas	1	1,030	1,135	1,369	1,572	5,500	1,624	61.6	1,556
Panhandle	Texas	6	640	710	—	—	2,785	597	167.6	944
Pierce Junction	Texas	3	—	1,663	—	—	4,303	1,486	67.3	1,769
Powell	Texas	14	1,147	1,347	1,460	—	2,950	1,460	68.5	2,254
Ranger	Texas	5	2,027	2,015	2,067	—	3,000	2,067	48.4	2,150
Rosewood	Texas	1	1,950	—	—	—	1,500	2,027	49.3	2,320
Sherman	Texas	2	1,460	—	—	—	1,450	1,388	72.0	1,379

TABLE I (*Continued*)

Town	*State*	*No. of Wells*	*b*×10⁵. Degrees F. per Foot				*Total Depth Feet*	*b*×10⁵ 100–Total Depth	1/*b* 100–Total Depth Ft.°F.	*b*×10⁵ 0–Total Depth
			100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet				
St. Jo	Texas	1	1,160	—	—	—	1,729	1,190	84.1	1,029
Thrifty	Texas	1	1,640	—	—	—	1,250	1,624	61.6	1,872
Waco	Texas	2	1,964	1,734	—	—	1,990	1,734	57.7	2,000
Wolfe City	Texas	2	1,823	—	—	—	1,700	1,973	50.7	1,982
Wortham	Texas	2	1,993	1,974	—	—	2,900	1,954	51.2	2,303
Benton City	Washington	1	2,265	2,085	—	—	2,200	2,064	48.5	2,282
Moclips	Washington	1	985	1,239	1,342	—	3,500	1,378	72.6	1,243
Seattle	Washington	1	929	971	—	—	2,500	949	105.4	820
Bridgeport	West Virginia	1	1,167	1,007	1,047	1,100	7,310	1,401	71.4	1,456
Fairmont	West Virginia	1	1,243	1,232	1,290	1,285	7,500	1,521	65.8	1,544
Grantsville	West Virginia	1	1,152	1,110	1,130	1,165	4,500	1,204	83.1	1,258
Mannington	West Virginia	1	1,371	1,140	1,105	—	3,225	1,096	91.2	1,101
Spencer	West Virginia	2	980	922	999	—	6,500	1,293	77.3	1,246
Volcano Junction	West Virginia	1	882	1,076	1,259	1,389	4,250	1,437	69.6	1,393
Volcano	West Virginia	1	860	1,081	1,267	1,411	4,400	1,476	67.8	1,448
Wheeling	West Virginia	1	—	1,180	1,186	—	4,462	1,349	74.2	1,268
Wyatt	West Virginia	1	1,085	1,018	—	—	2,000	1,018	98.2	1,065
Big Muddy	Wyoming	4	1,416	1,475	1,707	—	3,000	1,707	58.6	1,987
Cody	Wyoming	2	1,607	1,726	1,743	1,707	4,250	1,698	58.9	1,854
Grass Creek	Wyoming	3	—	—	—	—	800	1,934	51.7	1,988
Lance Creek	Wyoming	3	2,341	2,643	2,718	—	3,000	2,718	36.8	2,797
Lost Soldier	Wyoming	3	3,176	2,916	2,638	—	3,400	2,569	38.9	2,635
Pine Mountain	Wyoming	1	2,555	2,207	—	—	2,240	2,057	48.6	1,911
Rawlins	Wyoming	4	1,378	1,708	—	—	2,000	1,708	58.6	1,760
Rock River	Wyoming	3	1,343	—	1,431	—	3,000	1,431	69.9	1,540

TABLE I (*Continued*)

Town	State		No. of Wells	$b\times10^5$. Degrees F. per Foot				Total Depth Feet	$b\times10^5$ 100–Total Depth	$1/b$ 100–Total Depth Ft. °F.	$b\times10^5$ 0–Total Depth
				100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet				
Salt Creek	Wyoming		21	1,606	1,952	—	—	2,650	2,079	48.1	2,102
Tea Pot	Wyoming		1	2,232	2,551	—	—	2,736	2,744	36.4	2,727
Thermopolis	Wyoming		9	—	—	—	—	900	4,206	23.8	4,711*
Thermopolis (Gebo)	Wyoming		1	1,772	—	—	—	1,407	1,945	51.4	2,395
Thermopolis (Little Sand Draw)	Wyoming		1	1,457	1,506	1,612	—	3,000	1,612	62.9	1,723
A. Arithmetic mean. All values included. Formula 7		n	658	139	102	60	22	155	155		155
		b		.01559	.01606	.01556	.01433		.01720		.01811
		r		.00474	.00400	.00353	.00264		.00524		.00619
		r_0		.00040	.00040	.00046	.00056		.00042		.00050
		$1/b$		64.13	62.28	64.28	69.77		58.14		55.23
		m						2,781			
B. Arithmetic mean. Values for which $v \lesseqgtr 5r$ have been rejected. Formula 7		n	645	138	102	60	22		151		151
		b		.01534	.01606	.01556	.01433		.01636		.01702
		r		.00429	.00400	.00353	.00264		.00391		.00402
		r_0		.00036	.00040	.00046	.00056		.00032		.00033
		$1/b$		65.21	62.28	64.28	69.77		61.12		58.77
C. Arithmetic mean. Values for which $b \lesseqgtr 0.02470$ have been rejected. $1/b \lesseqgtr 40.49$. Formula 7		n	627	126	96	56	22		142		142
		b		.01414	.01533	.01474	.01433		.01567		.01634
		r		.00351	.00358	.00295	.00264		.00358		.00369
		r_0		.00031	.00036	.00039	.00056		.00030		.00031
		$1/b$		70.71	65.23	67.84	69.77		63.83		61.18
D. Weighted means of *A*-values. Formula 8		n	658						155		155
		b							.01645		.01707
		$1/b$							60.80		58.59

TABLE I (*Continued*)

Town	State		No. of Wells	$b \times 10^5$. Degrees F. per Foot				Total Depth Feet	$b \times 10^5$ / 100–Total Depth	$1/b$ / 100–Total Depth Ft. °F.	$b \times 10^5$ / 0–Total Depth
				100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet				
E. Weighted mean of *B*-values. Formula 8		*n*	645						151		151
		b							.01623		.01680
		$1/b$							61.63		59.53
F. Weighted mean of *C*-values. Formula 8		*n*	627						142		142
		b							.01549		.01608
		$1/b$							64.56		62.20
G. Equal weights. *A*-values. Formula 9		*n*	658								155
		b									.01654
		$1/b$									60.46
H. Equal weights. *B*-values. Formula 9		*n*	645								151
		b									.01647
		$1/b$									60.72
I. Weighted mean of *A*-values. Weights determined from Formula 12		*n*	658	139	102	60	22		155		
		b		.01560	.01594	.01514	.01392		.01583		
		$1/b$		64.11	62.72	66.04	71.84		63.19		
J. Weighted mean of *A*-values. Weights vary inversely as the squares of the probable errors		*n*	658	139	102	60	22		155		
		b		.01255	.01302	.01293	.01341		.01302		
		$1/b$		79.66	76.79	77.36	74.56		76.81		

* Theoretically rejected observations.

type, the reciprocal gradients increase with depth, whereas in curves of the convex type just the reverse condition exists. Thus in the latter case, the reciprocal gradients diminish from 116.3 to 67.8; in the former, they increase from 38.8 to 56.0 feet per degree Fahrenheit. In some fields, the predominating curve is a combination of curves of the concave and convex type.

TABULATIONS OF DATA

The gradients (b) in Table I are tabulated for different groups of depths, namely, 100 to 1,000 feet; 100 to 2,000 feet; and so on. This means that the constants in the straight line equation, $y=a+bx$, have been computed for each group of observations. In the first group, only those curves are included which reach a depth of 1,000 feet or more. Curves of depth less than 1,000 feet are included in the column designated "*100—Total Depth.*" The columns marked "*100–2,000* feet" include all curves that reach a depth of 2,000 feet or more, and so on for the 3,000- and 4,000-foot columns.

The gradients tabulated in the column, "*100—Total Depth,*" are obtained by making a least-square adjustment of a straight line (*dd* or *ff*) through all of the points on the curve. In the following column, the values of $1/b$, the reciprocal gradient, are given in feet per degree Fahrenheit. In the last column, the gradients have been computed from the annual mean temperature of the air (*g*, Fig. 2) and the single observation at the greatest depth in the well. As the annual mean temperature of the soil just beneath the surface of the ground must exceed the annual mean temperature of the air just above the surface of the ground, the constant value, 1°F., was added to the annual mean temperature of the air as interpolated from the volume on *Climatological Data of the United States Weather Bureau.* This value of the excess of soil temperature over air temperature was adopted by the Committee on Underground Temperatures of the British Association for the Advancement of Science in its report for the year 1882. The excess varies somewhat from place to place. An average value of 1.54°F. has been deduced from 514 tests in the United States (3). The values of the gradient in the last column are subject therefore to revision when the values of the excess of soil temperature over air temperature and the annual mean temperature of the air at the station are known more accurately; but the remaining tabulations of the gradients, being obtained from least-square adjustments of the original observations, are not subject to revision.

ERRORS IN GRADIENTS

A word of caution should be spoken in regard to errors in the observations. For example, the curves in Figure 2 are excellent examples of precise measurement; nevertheless, the resulting gradients may be incorrect. The flattening of the Shumway curve as it enters the granite at a depth of about 2,700 feet is to be expected for the reason that granite is a better conductor of heat than sedimentary deposits. The extreme curvature, however, may be the result of swabbing oil from the well a few hours before the test was made. The extreme convexity of the Volcano well is due in part to surface topography. Unstable temperature equilibrium is a disturbing factor in a large number of the wells. As it is impossible to eliminate these errors and irregularities, it is necessary to bear in mind that our final determinations are to be regarded as rather rough approximations to the true values. Definitive determinations can not be obtained from existing data.

FORMULAS FOR AVERAGING GRADIENTS

It is impossible to correctly interpret the numerous averages of gradients that can be obtained without the assistance of mathematical analysis. In order, therefore, that we may properly interpret our results, let us consider the significance of the formulas by means of which the averages have been obtained.

Let us put,

y_1 = rise in temperature from a point just beneath surface of ground to depth x_1 in well A_1

y_2 = same for depth x_2 in well A_2

. . . . . .

y_n = same for depth x_n in well A_n

Also, let us put for the residuals (v),

$v_1 = y_1 -$ computed value of y_1

$v_2 = y_2 -$ computed value of y_2

. . . . . .

$v_n = y_n -$ computed value of y_n.

Then we have by definition:

$$\begin{aligned} b &= y_1/x_1 = \text{gradient in well } A_1 \\ b &= y_2/x_2 = \text{gradient in well } A_2 \\ &\cdots\cdots\cdots\cdots \\ b &= y_n/x_n = \text{gradient in well } A_n \end{aligned} \qquad (1)$$

The arithmetic mean of the gradients is

$$b = \frac{y_1/x_1 + y_2/x_2 + \cdots y_n/x_n}{n} \tag{2}$$

and assuming that the weight of each value of b is proportional to the depth, we have from 1,

$$x_1 b = y_1 \qquad x_2 b = y_2 \cdots x_n b = y_n$$

which gives for the weighted mean,

$$b = \frac{y_1 + y_2 + \cdots y_n}{x_1 + x_2 + \cdots x_n}. \tag{3}$$

Equations 2 and 3 are the ones in general use. In order to determine the real significance of these equations, let us consider the adjustment of a straight line through the origin. Let it be assumed that we have n observation equations:

$$\begin{aligned} x_1 b &= y_1 \text{ weight } p_1 \\ x_2 b &= y_2 \text{ weight } p_2 \\ &\cdots\cdots\cdots \\ x_n b &= y_n \text{ weight } p_n \end{aligned} \tag{4}$$

the solution of which by the method of least squares gives

$$b = \frac{p_1 x_1 y_1 + p_2 x_2 y_2 + \cdots p_n x_n y_n}{p_1 x_1^2 + p_2 x_2^2 + \cdots p_n x_n^2}, \tag{5}$$

the residuals (v_1, v_2, . . . v_n) being subject to the condition

$$p_1 x_1 v_1 + p_2 x_2 v_2 + \cdots p_n x_n v_n = 0 \tag{6}$$

Following are important special cases of 5:

$$b = \frac{y_1/x_1 + y_2/x_2 + \cdots y_n/x_n}{n} \qquad p_1 = \frac{1}{x_1^2} \; p_2 = \frac{1}{x_2^2} \cdots p_n = \frac{1}{x_n^2} \tag{7}$$

$$b = \frac{y_1 + y_2 + \cdots y_n}{x_1 + x_2 + \cdots x_n} \qquad p_1 = \frac{1}{x_1} \; p_2 = \frac{1}{x_2} \cdots p_n = \frac{1}{x_n} \tag{8}$$

$$b = \frac{x_1 y_1 + x_2 y_2 + \cdots x_n y_n}{x_1^2 + x_2^2 + \cdots x_n^2} \qquad p_1 = p_2 = \cdots p_n \tag{9}$$

$$b = \frac{x_1^2 y_1 + x_2^2 y_2 + \cdots x_n^2 y_n}{x_1^3 + x_2^3 + \cdots x_n^3} \qquad p_1 = x_1 \; p_2 = x_2 \cdots p_n = x_n \tag{10}$$

Equations 7 and 8 are the same as equations 2 and 3. Since the weights vary inversely as the squares of the probable errors, it follows that in equations 2 and 7, the errors of the observed temperatures are proportional to the depths, whereas in equations 3 and 8 the errors are proportional to the square roots of the depths. Equation 9 amounts to assuming that the errors in the temperature readings at the various depths are the same. In 10, the errors are assumed to vary inversely as the square root of the depth, that is, the errors of the observed temperatures are supposed to diminish with the depth. There is no justification for this assumption, but equations 7, 8, 9, in which the errors are supposed to be independent of the depth 9, or to increase linearly with the depth 7, or the square root of the depth 8, rest on a sufficiently sound basis to justify their use. Equation 6 is a partial check on the calculations.

When the observations in the different wells are made at the same depth (x_1), equations 7, 8, 9, 10 reduce to

$$b = \frac{y_1/x_1 + y_2/x_2 + \cdots y_n/x_n}{n},$$

the arithmetic mean of the gradients. Equation 6 shows that the sum of the residuals vanishes for these special cases. That is,

$$v_1 + v_2 + \cdots v_n = 0$$

Formulas 7, 8, 9 are applicable to the data in the last column of Table I. In the remaining tabulations of b in Table I, the values have been determined from a series of n' observed temperatures in the same well by making a least-square solution of the n' observation equations:

$$\begin{aligned} a + x_1 b &= y_1 \\ a + x_2 b &= y_2 \\ &\cdots\cdots \\ a + x_n' b &= y_n' \end{aligned} \qquad (11)$$

where y is now the observed temperature at depth x; a is the intercept of the straight line on the y-axis; and b is the computed gradient.

The least-square solution of equations 11 gives the normal equations:

$$\begin{aligned} n'a + (\Sigma x)b &= \Sigma y \\ (\Sigma x)a + (\Sigma x)^2 b &= \Sigma xy \end{aligned}$$

from which the values of a and b can be obtained by algebraic methods. The weights of a and b are respectively:

$$p_a = n' - \frac{(\Sigma x)^2}{\Sigma x^2} \qquad p_b = \Sigma x^2 - \frac{(\Sigma x)^2}{n'}. \tag{12}$$

In these equations,

$$\Sigma x = x_1 + x_2 + \cdots x_n'$$
$$\Sigma y = y_1 + y_2 + \cdots y_n'$$
$$\Sigma xy = x_1y_1 + x_2y_2 \cdots x_n'y_n'$$
$$\Sigma x^2 = x_1^2 + x_2^2 + \cdots x_n'^2$$

Equation 12 shows that the weight of b is dependent on n', the number of observed points in the well, and also on the distribution of these points in the well.

AVERAGES DEDUCED FROM TABLE I

The summary at the end of Table I shows that it is based on a total of 658 wells. The total number of fields and single locations represented is 155. Out of this total of 155 wells, 139 wells reached a depth of 1,000 feet; 102 wells reached a depth of 2,000 feet; and so on for the other depths. The average depth (m) of the 155 wells is 2,781 feet. In fields in which there are more than one well, that well has been selected in which the gradient is a minimum or the reciprocal gradient is a maximum. When there is precise correlation of temperature with structure, the well thus selected is, of course, the lowest on the structure.

Comparison of the values of $1/b$ in the last column of the summary with the tabulations in the third from the last column shows without exception that the smaller values are always found in the last column. The reciprocal of the mean of 6 average values of the gradient in the second from the last column is 61.60; in the last, 59.16, leaving a difference of 2.44 feet per degree Fahrenheit. This difference is readily explained. Referring to Figure 2, it will be seen that a straight line drawn from g, or, more accurately, from a point 1°F. above g, to the 4,400-foot point on curve BB', makes a greater angle with the depth-axis than the straight line ff which is adjusted by the method of least squares to all of the points on the curve BB'. The reverse condition exists for the concave curves AA', but the convex curves outnumber the concave curves about 2 to 1; consequently, the average for a number of curves reflects the more rapid rise of the convex curves.

However, the mean difference of only 2.44 feet per degree Fahrenheit is small and indicates that the total error introduced into the mean by the use of either method is not particularly serious.

The calculations carried out to obtain the results in the last column of the table are the same as those by means of which the Committee on Underground Temperature of the British Association for the Advancement of Science (Report 1882, page 88) obtained the value of 64 feet per degree Fahrenheit. The calculations (Formula 8) were based on 36 observations in Europe, chiefly in mines and artesian wells. As a result of correcting the gradients in Mont Cenis and St. Gothard tunnels, the Report of the Committee for the year 1883 (page 49) contains the value of 1°F. in 60 feet. The fact that two corrections in the British data change the rate of temperature increase by 4 feet per degree is an indication that averages taken in this way are not altogether reliable. The defect in this method of averaging is due to the fact that the observations are not sufficiently representative of the different geological conditions. With a few observations on each of a very great number of different geological units distributed over a large area, the values would tend to be consistent. This definition of a normal gradient corresponds to the mathematical definition in which the number of gradients in a large area is infinite, or, from a practical standpoint, very large.

Strict compliance with the mathematical requirements is impossible. The next best method of procedure is to obtain as much information as possible from a limited number of observations by means of the mathematical theory of probability and least-square adjustments of the data of observation.

The curvature of the depth-temperature curves greatly complicates the problem of evaluating a theoretically correct average or normal gradient. If the depth-temperature curves were straight lines, the weight of b would be given correctly by the well known relation that the weights are inversely proportional to the squares of the probable errors, the latter being obtained rigorously from the usual least-square adjustment of the straight line, $y=a+bx$, to the observed temperatures at the given series of depths. The curves in Figure 2 show that the residuals ($v=ll$) are very large in comparison with the errors of observation. This method, therefore, assigns minimum weights to curves of maximum curvature, disregarding, for the most part, the accuracy of the observations. Furthermore, the value of the gradient itself varies rapidly with the depth. When the range of depths is large, as in the last two columns of tabular values of b, the resulting average gradient is difficult of correct interpretation. For

this reason, no further consideration will be given the tabulations in these two columns in attempting to deduce an average gradient from the data of observation.

In group *J*, where the weights are inversely proportional to the squares of the probable errors, the resulting values are not in agreement with those obtained by means of formulas 7, 8, 9. From what has just been said in regard to the effect of the curvature of the depth-temperature curves on the weights of the gradients, it follows that the results summarized in the *J*-groups are dependent chiefly on those depth-temperature curves which approach a straight line.

In the last column are shown the different results obtained by the use of formulas 7, 8, 9. The mean values are not very consistent and differ widely from those given in the *J*-group. The inconsistencies emphasize the importance of assigning theoretically correct weights to the individual values. Formula 9 is the correct formula to use when true rock temperatures are recorded at a single point in each well.

In group *I*, the weights have been computed from Formula 12. Since the observations have generally been made at practically the same points, 100, 250, 500, . . . feet, the values of the weights deviate only slightly from constancy, except for the column of total depth. It is to be expected, therefore, that the mean values in the first four columns of the *I*-group will approximate closely to those found in the *A*-group. Comparison of the results shows a sufficiently close agreement with theory. In comparison with the *J*-group, it amounts to assuming that r, the probable error of an observation of weight unity in the *J*-group, is equal to a constant.

In the *B*-group, those values of the gradient for which v, the deviation from the mean, equals or exceeds $5r$ have been rejected. This procedure is based on the statistical deduction that there is only 1 chance in about 1,000 that any individual residual in a statistical system should equal or exceed $5r$. The rule is a very useful guide. Like other statistical deductions, it is not absolute. The summary shows that one value in the first column and four in the last two columns were rejected. The rejected values are indicated by an asterisk in the main part of the table.

In group *C* all values of b for which the reciprocal gradient in the *B*-group exceeds 1°F. in about 40 feet have been arbitrarily rejected. The object of this procedure is to eliminate the abnormally high values of the gradients which are frequently found in the oil fields. The table shows that the reciprocal gradient for the first 1,000 feet is changed by this operation from 65.21 to 70.71 feet per degree Fahrenheit.

With the exception of the *C*-group and the *J*-group, the results for the range, 100–1,000 feet, are quite consistent. The means for the other three ranges of depth show irregularities that increase as the number of wells decreases. That is, these means show the effects of the areal distribution of the wells. The effect appears also in the range, 100–1,000 feet, but to a lesser degree on account of the greater number of wells.

AVERAGES DEDUCED FROM TABLES II AND III

Tables II and III have been constructed on the same general plan as Table I. The object of these tables is to take into account the variation of temperature with structure. Hence, in Table II, only those wells are considered that are highest on the structure. In Table III, the wells that are supposed to be lowest on the structure have been included. On account of irregularities in the observations, cases can be found in which the most rapid rate of temperature increase is not found on the crest of the structure; in fact, in a few instances, just the reverse of these conditions exists. In general, however, variation of temperature across a structure is much more probable than no variation, and in the observed exceptions to the rule, it is highly probable that a variation exists, so that the assumption of a variation regardless of the positions of the wells is a closer approximation to the facts than is the assumption that geothermal synclines stand in correlation with geological anticlines. Furthermore, exceptions in these cases are offset by numerous other cases, particularly in Wyoming and the salt-dome area of the Gulf Coast, where the lowest recorded gradient is high on the structure. For example, the highest reciprocal gradient recorded at Lance Creek, Wyoming, is 42.7 feet per degree Fahrenheit. As this well is near the top of the structure, it is not unreasonable to assume that the reciprocal gradients in the area surrounding Lance Creek are equal to or greater than 60 or 70 feet per degree. Hence, it is believed that the averages here obtained are approximately correct representations of the actual conditions to be expected on anticlines and domes.

The tables show that the mean depth of 63 wells on the crest of the structure is 2,316 feet; the same for 63 wells on the flank, is 2,489 feet. This shows that a majority of the wells in which there is a rapid rate of temperature increase are located on or near the crests of the structures.

Comparison of the last two columns of tabulations shows that Table III agrees with Table I in that minimum values of $1/b$ are found in the last column. The predominating curve represented in

TABLE II

GRADIENTS ON CREST OF STRUCTURE

Town	State	No. of Wells	$b \times 10^5$. Degrees F. per Foot				Total Depth Feet	$b \times 10^5$ 100–Total Depth	1/b 100–Total Depth Ft. °F.	$b \times 10^5$ 0–Total Depth
			100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet				
El Dorado	Arkansas	7	2,055	1,936	—	—	2,120	1,891	52.9	1,755
Bakersfield	California	5	1,532	1,624	—	—	2,850	1,666	60.0	1,884
Coalinga	California	51	2,289	1,792	—	—	1,954	1,792	55.8	2,201
Huntington Beach	California	4	2,503	—	—	—	1,000	2,503	40.1	3,060
Kettleman Hills	California	4	2,125	—	—	—	1,190	2,052	48.7	2,487
Long Beach	California	40	2,183	2,024	1,979	—	3,000	1,979	50.5	2,280
Santa Fe Springs	California	31	2,455	2,098	1,993	—	3,000	1,993	50.2	2,213
Whittier	California	4	1,774	1,824	1,835	—	3,500	1,842	54.3	2,117
Florence	Colorado	3	2,220	2,127	—	—	2,400	2,074	48.2	2,225
Fort Collins	Colorado	2	1,844	1,795	1,861	—	3,000	1,861	53.7	2,023
Bridgeport	Illinois	4	1,827	—	—	—	1,800	1,725	58.0	1,672
Augusta	Kansas	2	2,028	1,944	—	—	2,250	1,908	52.4	1,924
El Dorado	Kansas	24	2,167	2,046	—	—	2,250	2,017	49.6	1,920
Florence	Kansas	4	1,731	1,673	—	—	2,150	1,647	60.7	1,619
Haverhill	Kansas	3	1,967	1,906	—	—	2,250	1,936	51.6	1,973
Blue Lake	Louisiana	2	1,800	2,250	—	—	2,000	2,250	44.4	2,390
Caddo Lake (Pine Island)	Louisiana	5	2,845	2,451	2,269	—	3,500	2,218	45.1	2,237
Homer	Louisiana	8	3,023	—	—	—	1,300	3,006	33.3	2,692
Many	Louisiana	6	2,019	2,195	—	—	2,470	2,402	41.6	2,397
Zwolle	Louisiana	3	1,980	2,249	2,186	—	3,380	2,191	45.7	2,290
Kevin-Sunburst	Montana	10	1,399	—	—	—	1,250	1,442	69.4	1,584
Artesia	New Mexico	3	772	—	—	—	1,500	611	163.6	793
Ardmore	Oklahoma	4	831	881	978	—	3,000	978	102.3	1,010
Ardmore-Healdton	Oklahoma	9	1,265	—	—	—	1,000	1,265	79.0	1,240
Ardmore-Hewett	Oklahoma	8	1,152	—	—	—	1,000	1,152	86.8	820

TABLE II (*Continued*)

Town	State	No. of Wells	$b \times 10^6$. Degrees F. per Foot				Total Depth Feet	$b \times 10^6$ 100–Total Depth	1/b 100–Total Depth Ft. °F.	$b \times 10^6$ 0–Total Depth
			100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet				
Blackwell	Oklahoma	2	2,162	2,111	—	—	1,835	2,111	47.4	1,896
Braman	Oklahoma	3	2,462	—	—	—	1,375	2,313	43.2	1,891
Burbank	Oklahoma	3	2,363	2,114	—	—	2,750	2,144	46.6	2,236
Cromwell	Oklahoma	9	2,037	2,123	2,213	—	3,000	2,213	45.2	2,113
Dilworth	Oklahoma	11	2,045	—	—	—	1,766	2,082	48.0	2,027
Drumright	Oklahoma	28	1,826	—	—	—	1,315	1,940	51.5	1,947
Glenn Pool	Oklahoma	18	2,687	—	—	—	1,260	2,607	38.4	2,278
Okemah	Oklahoma	4	2,572	2,595	—	—	2,500	2,549	39.2	2,424
Oklahoma City	Oklahoma	3	784	829	885	933	4,000	933	107.1	953
Papoose	Oklahoma	4	2,136	2,240	—	—	2,750	2,367	42.3	2,222
Sasakwa	Oklahoma	2	1,646	1,769	1,842	—	3,500	1,878	53.3	1,869
Seminole	Oklahoma	19	1,530	1,734	—	—	2,500	1,789	55.9	1,672
Tonkawa	Oklahoma	15	1,944	1,866	—	—	2,820	1,910	52.4	1,947
Walters	Oklahoma	10	916	898	—	—	2,000	898	111.4	890
Wewoka	Oklahoma	5	2,255	2,167	2,066	—	3,000	2,066	48.4	2,067
Long Bridge	Pennsylvania	3	1,466	1,481	1,500	1,498	6,000	1,645	60.8	1,612
Big Lake	Texas	16	1,000	838	—	—	3,175	699	143.1	699
Blue Ridge	Texas	7	—	—	—	—	700	2,677	37.4	2,543
Boggy Creek	Texas	3	2,935	2,623	2,495	—	3,590	2,333	42.9	2,423
Graham	Texas	2	1,804	1,643	1,632	1,691	4,334	1,732	57.7	1,797
Grand Saline	Texas	4	—	—	—	—	200	4,000	25.0	3,850
Humble	Texas	28	4,613*	—	—	—	1,080	4,517	22.1	4,028
Long Point	Texas	8	—	—	—	—	857	3,715	26.9	3,617
Luling	Texas	4	2,305	2,238	—	—	2,000	2,238	44.7	2,265
Lytton Springs	Texas	7	2,636	—	—	—	1,175	2,559	39.1	2,536

TABLE II (*Continued*)

Town	State	No. of Wells	$b \times 10^6$. Degrees F. per Foot: 100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet	Total Depth Feet	$b \times 10^6$ 100–Total Depth	$1/b$ 100–Total Depth Ft. °F.	$b \times 10^6$ 0–Total Depth
Mexia	Texas	6	2,568	2,419	2,393	—	2,985	2,393	41.8	2,335
Pierce Junction	Texas	3	1,692	1,817	1,762	—	3,300	1,753	57.0	1,812
Powell	Texas	14	2,584	2,301	—	—	2,750	2,237	44.7	2,269
Ranger	Texas	5	2,347	2,216	2,230	—	3,000	2,230	44.8	2,273
Wortham	Texas	2	2,145	2,127	—	—	2,800	2,069	48.3	2,361
Big Muddy	Wyoming	4	1,886	1,792	1,880	—	3,250	1,884	53.1	1,954
Grass Creek	Wyoming	3	1,998	—	—	—	1,090	1,953	51.2	2,037
Lance Creek	Wyoming	3	2,469	2,718	2,728	—	3,500	2,720	36.8	2,843
Lost Soldier	Wyoming	3	5,300*	4,895	—	—	1,925	4,895	20.4	5,210
Rawlins	Wyoming	4	2,324	—	—	—	1,500	2,034	49.2	2,100
Rock River	Wyoming	3	1,802	—	—	—	2,700	1,918	52.1	1,926
Salt Creek	Wyoming	21	3,440	—	—	—	1,500	3,483	28.7	3,493
Thermopolis	Wyoming	9	4,784*	—	—	—	1,000	4,784	20.9	5,310
A. Arithmetic mean. All values included. Formula 7	n	544	60	41	19		3	63	63	63
	b		.02154	.02009	.01933		.01374		.02169	.02199
	r		.00567	.00436	.00313		.00266		.00561	.00577
	r_0		.00073	.00068	.00072		.00153		.00071	.00073
	$1/b$		46.42	49.78	51.73		72.78		46.10	45.48
	m							2,316		
B. Arithmetic mean. Values for which $v \leq 5r$ have been rejected from *A*. Formula 7	n	504	57	40	19	3		63		61
	b		.02010	.01937	.01933	.01374		.02169		.02099
	r		.00379	.00309	.00313	.00266		.00561		.00444
	r_0		.00050	.00049	.00072	.00153		.00071		.00059
	$1/b$		49.76	51.63	51.73	72.78		46.10		47.65

TABLE II (*Continued*)

Town	State		No. of Wells	$b \times 10^6$. Degrees F. per Foot				Total Depth Feet	$b \times 10^6$ / 100 − Total Depth	1/b / 100 − Total Depth Ft. °F.	$b \times 10^6$ / o − Total Depth
				100 − 1,000 Feet	100 − 2,000 Feet	100 − 3,000 Feet	100 − 4,000 Feet				
C. Arithmetic mean. Fields in which there are only 2 wells have been omitted from *B*. Formula 7		n	490	50	33	16	2		56		54
		b		.02022	.01934	.01962	.01216		.02194		.02107
		r		.00402	.00335	.00337	.00270		.00596		.00459
		r_0		.00057	.00058	.00084	.00191		.00080		.00062
		$1/b$		49.44	51.70	50.97	82.27		45.58		47.47
D. Weighted mean of *A*-values. Formula 8		n	544						63		63
		b							.02035		.02077
		$1/b$							49.15		48.15
E. Weighted mean of *B*-values. Formula 8		n	504						63		61
		b							.02035		.02012
		$1/b$							49.15		49.70
F. Weighted mean of *C*-values. Formula 8		n	490						56		54
		b							.02051		.02013
		$1/b$							48.77		49.68
G. Equal weights. *A*-values. Formula 9		n	544								63
		b									.02001
		$1/b$									49.99
H. Equal weights. *B*-values. Formula 9		n	504								61
		b									.01963
		$1/b$									50.95
I. Weighted mean of *A*-values. Weights determined from Formula 12		n	544	60	41	19	3		63		
		b		.02179	.02039	.01946	.01366		.01941		
		$1/b$		45.90	49.03	51.40	73.18		51.52		
J. Weighted mean of *A*-values. Weights vary inversely as the square of the probable errors		n	544	60	41	19	3		63		
		b		.02098	.01740	.01793	.01426		.02295		
		$1/b$		47.67	57.47	55.77	70.10		43.57		

* Theoretically rejected observations.

TABLE III

GRADIENTS ON FLANK OF STRUCTURE

Town	State	No. of Wells	$b \times 10^5$. Degrees F. per Foot				Total Depth Feet	$b \times 10^5$	$1/b$	$b \times 10^5$
			100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet		100–Total Depth	100–Total Depth Ft.°F.	0–Total Depth
El Dorado	Arkansas	7	1,862	2,329	—	—	2,000	2,329	42.9	2,240
Bakersfield	California	5	1,198	1,236	1,338	1,464	4,250	1,569	63.7	1,911
Coalinga	California	51	1,413	—	—	—	1,370	1,351	74.0	1,956
Huntington Beach	California	4	2,225	2,456	2,624	—	3,500	2,643	37.8	2,786
Kettleman Hills	California	4	1,612	—	—	—	1,350	1,671	59.9	2,244
Long Beach	California	40	1,607	1,681	—	—	2,500	1,642	60.9	2,204
Santa Fe Springs	California	31	1,535	1,819	1,895	—	4,250	1,904	52.5	1,995
Whittier	California	4	1,670	1,809	1,885	—	3,750	1,874	53.4	2,136
Florence	Colorado	3	1,532	1,848	—	—	2,900	2,020	49.5	2,090
Fort Collins	Colorado	2	1,667	1,755	1,858	1,956	4,000	1,956	51.1	2,050
Bridgeport	Illinois	4	1,456	—	—	—	1,250	1,526	65.5	1,704
Augusta	Kansas	2	1,945	2,009	—	—	2,250	1,984	50.4	2,013
El Dorado	Kansas	24	1,777	1,827	—	—	2,250	1,799	55.6	1,689
Florence	Kansas	4	1,361	—	—	—	1,750	1,590	62.9	1,686
Haverhill	Kansas	3	1,720	1,819	—	—	2,750	1,783	56.1	1,811
Blue Lake	Louisiana	2	1,786	—	—	—	1,500	1,993	50.2	2,180
Caddo Lake	Louisiana	5	2,653	2,423	—	—	2,000	2,423	41.3	2,325
Homer	Louisiana	8	2,518	—	—	—	1,150	2,646	37.8	2,357
Many	Louisiana	6	1,883	—	—	—	1,250	1,926	51.9	1,832
Zwolle	Louisiana	3	1,751	—	—	—	1,250	1,771	56.5	1,792
Kevin-Sunburst	Montana	10	930	978	987	—	3,000	987	101.4	1,123
Artesia	New Mexico	3	560	478	—	—	2,892	439	227.7	598
Ardmore	Oklahoma	4	657	—	—	—	1,500	678	147.5	667
Ardmore-Healdton	Oklahoma	9	616	—	—	—	1,500	657	152.2	593
Ardmore-Hewett	Oklahoma	8	808	—	—	—	1,750	950	105.3	800

TABLE III (*Continued*)

Town	State	No. of Wells	$b \times 10^5$. Degrees F. per Foot				Total Depth Feet	$b \times 10^5$	$1/b$	$b \times 10^5$
			100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet		100–Total Depth	100–Total Depth Ft.°F.	0–Total Depth
Blackwell	Oklahoma	2	2,038	2,027	—	—	2,000	2,027	49.3	1,900
Braman	Oklahoma	3	1,758	—	—	—	1,410	1,829	54.7	1,787
Burbank	Oklahoma	3	1,893	2,093	—	—	2,850	2,188	45.7	2,172
Cromwell	Oklahoma	9	1,886	—	—	—	1,200	1,918	52.1	1,775
Dilworth	Oklahoma	11	1,743	1,848	1,874	—	3,000	1,874	53.4	1,953
Drumright	Oklahoma	28	880	1,381	—	—	2,210	1,467	68.2	1,416
Glenn Pool	Oklahoma	18	2,284	—	—	—	1,500	2,383	42.0	2,187
Okemah	Oklahoma	4	2,341	2,240	—	—	2,500	2,241	44.6	2,444
Oklahoma City	Oklahoma	3	659	765	841	904	4,000	904	110.7	1,023
Papoose	Oklahoma	4	1,903	1,945	—	—	2,500	2,014	49.7	2,168
Sasakwa	Oklahoma	2	1,326	1,480	—	—	2,620	1,518	65.9	1,443
Seminole	Oklahoma	19	1,019	1,314	—	—	2,750	1,340	74.6	1,284
Tonkawa	Oklahoma	15	1,569	1,831	—	—	2,750	1,840	54.3	1,876
Walters	Oklahoma	10	750	—	—	—	2,150	864	115.7	902
Wewoka	Oklahoma	5	1,951	2,063	2,107	—	3,000	2,107	47.5	2,087
Long Bridge	Pennsylvania	3	1,370	1,473	1,480	1,482	6,500	1,674	59.7	1,634
Big Lake	Texas	16	672	—	—	—	1,500	636	157.3	873
Blue Ridge	Texas	7	—	1,706	—	—	2,900	1,800	55.6	1,828
Boggy Creek	Texas	3	—	2,499	2,820	—	3,703	2,867	34.9	2,768
Graham	Texas	2	1,502	1,630	1,638	—	3,000	1,638	61.0	1,830
Grand Saline	Texas	4	—	—	—	—	875	1,606	62.2	1,977
Humble	Texas	28	1,458	1,677	—	—	2,000	1,677	59.6	1,560
Long Point	Texas	8	1,789	1,831	1,777	—	3,300	1,765	56.7	1,794
Luling	Texas	4	1,489	1,832	—	—	2,500	1,886	53.0	2,184
Lytton Springs	Texas	7	2,464	—	—	—	1,350	2,297	43.5	2,356

TABLE III (*Continued*)

Town	State	No. of Wells	$b \times 10^5$. Degrees F. per Foot: 100–1,000 Feet	100–2,000 Feet	100–3,000 Feet	100–4,000 Feet	Total Depth Feet	$b \times 10^5$: 100–Total Depth	$1/b$: 100–Total Depth Ft.°F.	$b \times 10^5$: 0–Total Depth
Mexia	Texas	6	1,820	2,072	—	—	2,900	2,099	47.6	2,369
Pierce Junction	Texas	3	—	1,663	—	—	4,303	1,486	67.3	1,769
Powell	Texas	14	1,147	1,347	1,460	—	2,950	1,460	68.5	2,254
Ranger	Texas	5	2,027	2,015	2,067	—	3,000	2,067	48.4	2,150
Wortham	Texas	2	1,993	1,974	—	—	2,900	1,954	51.2	2,303
Big Muddy	Wyoming	4	1,416	1,475	1,707	—	3,000	1,707	58.6	1,987
Grass Creek	Wyoming	3	—	—	—	—	800	1,934	51.7	1,988
Lance Creek	Wyoming	3	2,341	2,643	2,718	—	3,000	2,718	36.8	2,797
Lost Soldier	Wyoming	3	3,176	2,916	2,638	—	3,400	2,569	38.9	2,635
Rawlins	Wyoming	4	1,378	1,708	—	—	2,000	1,708	58.6	1,760
Rock River	Wyoming	3	1,343	—	1,431	—	3,000	1,431	69.9	1,540
Salt Creek	Wyoming	21	1,606	1,952	—	—	2,650	2,079	48.1	2,102
Thermopolis	Wyoming	9	—	—	—	—	900	4,206	23.8	4,711*
A. Arithmetic mean. All values included. Formula 7	n	544	57	42	19	4	63	63		63
	b		.01609	.01806	.01850	.01452		.01808		.01911
	r		.00368	.00317	.00376	.00290		.00403		.00421
	r_0		.00049	.00049	.00086	.00086		.00051		.00053
	$1/b$		62.14	55.36	54.06	68.89		55.32		52.34
	m						2489			
B. Arithmetic mean. Values for which $v \overline{>} 5r$ have been rejected from *A*. Formula 7	n	535	57	42	19	4		62		62
	b		.01609	.01806	.01850	.01452		.01769		.01865
	r		.00368	.00317	.00376	.00290		.00349		.00347
	r_0		.00049	.00049	.00086	.00086		.00044		.00044
	$1/b$		62.14	55.36	54.06	68.89		56.53		53.61
C. Arithmetic mean. (Fields in which there are only 2 wells have been omitted from *B*.) Formula 7	n	521	50	36	17	3		55		55
	b		.01590	.01805	.01862	.01283		.01757		.01853
	r		.00387	.00338	.00397	.00222		.00367		.00363
	r_0		.00055	.00056	.00096	.00128		.00050		.00049
	$1/b$		62.91	55.39	53.71	77.92		56.93		53.95

TABLE III (*Continued*)

Town	*State*		*No. of Wells*	$b \times 10^5$. *Degrees F. per Foot*				*Total Depth Feet*	$b \times 10^5$	$1/b$	$b \times 10^5$
				100–1,000 Feet	*100–2,000 Feet*	*100–3,000 Feet*	*100–4,000 Feet*		*100–Total Depth*	*100–Total Depth Ft.°F.*	*0–Total Depth*
D. Weighted mean of *A*-values. Formula 8		*n*	544						63		63
		b							.01799		.01907
		$1/b$							55.59		52.44
E. Weighted mean of *B*-values. Formula 8		*n*	535						62		62
		b							.01785		.01891
		$1/b$							56.02		52.89
F. Weighted mean of *C*-values. Formula 8		*n*	521						55		55
		b							.01776		.01882
		$1/b$							56.31		53.14
G. Equal weights. *A*-values. Formula 9		*n*	544								63
		b									.01907
		$1/b$									52.44
H. Equal weights. *B*-values. Formula 9		*n*	535								62
		b									.01902
		$1/b$									52.58
I. Weighted mean of *A*-values. Weights determined from Formula 12		*n*	544	57	42	19	4		63		
		b		.01618	.01824	.01856	.01463		.01790		
		$1/b$		61.79	54.82	53.88	68.35		55.87		
J. Weighted mean of *A*-values. Weights vary inversely as the square of the probable errors		*n*	544	57	42	19	4		63		
		b		.01322	.01559	.01627	.01454		.01436		
		$1/b$		75.63	64.13	61.46	68.76		69.64		

* Theoretically rejected observations.

these columns is therefore of the convex type. In Table II, the reciprocal gradients tabulated in the last column of averages are generally larger than those of the next adjacent column. This implies a predominance of straight lines and concave curves, as might be expected from the shallower depths and the more rapid approach of the wells to granite on the crests of the structures.

The results assembled in Table II are quite consistent; even the *J*-group which is abnormal in the other two tables is here in fair agreement with the other means. The agreement is not a coincidence. It is due to the fact, as previously stated, that the weights in the *J*-group are more and more in agreement with theory as the depth-temperature curves approach straight lines.

The arbitrary rejection of a total of 7 fields in each of which there are only 2 wells, group *C*, does not seriously affect the results obtained on either the crests or the flanks of the structures.

REJECTED OBSERVATIONS

Theoretically rejected observations in all of the tables have been indicated by an asterisk. Rejections occur in Oregon, Texas, and Wyoming. The Oregon data are based on temperature measurements that are sufficiently precise, but on account of the irregularly shaped depth-temperature curves, it is difficult to determine a representative gradient from them. The one gradient in the entire list that is most likely to be incorrect is the one at Albany, Alabama. Here the measurements were made in an uncased well which was 12.5 inches in diameter at the top and 8 inches in diameter at 2,000 feet. The rise in the depth-temperature curve to a depth of 750 feet is almost imperceptible. The results suggest a circulation of water either by convection or by the movement of water from one bed to another. Theoretical calculations do not indicate that this well should be rejected. The other wells that appear in the list of rejections represent extreme geological conditions. They can not be rejected on the basis of errors of observation.

INTERPRETATION OF TABLES I, II, AND III

Excluding from Table I the Albany well and the wells that are known to be in proved or prospective oil fields, we have the following series of gradients from the first three columns of tabulations:

	100–1,000 Feet	*100–2,000 Feet*	*100–3,000 Feet*
Birmingham	0.00914	0.00955	—
Grass Valley	0.00593	0.00569	0.00537
Ames	0.00695	0.00731	—
Houghton	0.00771	—	—
Franklin Furnace	0.00362	—	—
Lonetree	0.01578	0.01654	0.01806
Astoria	0.01503	0.01615	0.01656
Moclips	0.00985	0.01239	0.01342
Seattle	0.00929	0.00971	—
b	0.00926	0.01105	0.01335
$1/b$	108.04	90.51	74.89

Comparison of these values with the corresponding values in Tables I, II, and III, shows that the mean gradients recorded in the tables are determined almost entirely by the much larger values of the gradients found in most of the oil-bearing areas.

TABLE IV

RATIOS OF GRADIENTS

	2,000/1,000	*3,000/1,000*	*4,000/1,000*	*Remarks*
n	97	55	20	
m	1.0523	1.0928	1.1928	Table I
r	0.0927	0.1197	0.1829	
r_0	0.0094	0.0161	0.0409	
b	0.01614	0.01676	0.01830	
$1/b$	61.95	59.65	54.65	
n	95			Table II
m	1.0417			
r	0.0793			
r_0	0.0081			
b	0.01598			
$1/b$	62.58			
n	41	19	3	Table III
m	0.9838	0.9944	1.0497	
r	0.0609	0.0753	0.0869	
r_0	0.0095	0.0173	0.0502	
b	0.01977	0.01999	0.02110	
$1/b$	50.57	50.03	47.40	
n	39	18	4	Table III
m	1.0974	1.1104	1.2122	
r	0.0842	0.0721	0.0818	
r_0	0.0135	0.0170	0.0409	
b	0.01766	0.01787	0.01950	
$1/b$	56.63	55.97	51.27	
n	38			Table III
m	1.0850			
r	0.0669			
r_0	0.0108			
b	0.01746			
$1/b$	57.28			

In the preceding summary, the values of $1/b$ diminish uniformly with the depth. This is not the case in Tables I, II, and III. The discrepancies are the results of areal distribution of the wells. Table IV shows the results of attempting to eliminate these inconsistencies. In this table, the mean (m) of the ratios of the gradients for the different depths to the gradient computed for the first 1,000 feet has been tabulated.

The first part of the table shows that the mean of 97 ratios of the gradients from 100 to 2,000 feet to the gradients from 100 to 1,000 feet is 1.0523, the probable errors being represented as heretofore by r and r_0, the latter being the probable error of the mean. Multiplying the mean ratio, 1.0523, by 0.01534, the value of b in the B group, Table I, we have for the mean gradient from 100 to 2,000 feet, the value, 0.01614, corresponding with the reciprocal gradient 1°F. in 61.95 feet. The numbers in the remaining columns are computed in a similar manner. Two rejections occur in the first column of tabular results. The final sequence in the values of the reciprocal gradients, namely, 65.21, 62.58, 59.65, 54.65, shows that the normal curve is convex to the depth axis. The summary for Table III—62.14, 57.28, 55.97, 51.27—shows a similar sequence, but the numerical values of the reciprocal gradients are greatly diminished, again showing the influence of the higher temperatures in the oil fields. The sequence for Table II—49.76, 50.57, 50.03, 47.40—shows that an average of the depth-temperature curves on the crests of anticlines tends to approximate rather closely to a straight line.

Summarizing the results of Table IV with reference to Tables II and III, we can say that the convexity of the depth-temperature curves increases as we pass from the crest to the flank of the structure. This experimental result is partly accidental, but it follows, also, from the geometry of the isogeotherms. Thus, for convenience, let it be assumed that $a''a'a$ and $c''c'c$ (Fig. 1) are isogeotherms. Then the gradients are determined by the constant difference in temperature between the two isogeotherms divided by the lengths ac, $a'c'$, $a''c''$. Since $a'c'$ is greater than ac, it follows that the gradient at $a'c'$ is less than at ac; but, since the temperatures must be the same at the depth at which the isogeotherms become parallel to a horizontal surface, it follows that the temperatures must increase much more rapidly along $a'c'$ extended than along ac extended. Hence the convexity of the depth-temperature curve $a'c'$ is greater than that of ac.

Comparison of the B groups in Tables II and III shows that the reciprocals of the mean gradients vary from 49.76 on the crest to 62.14 on the flank of the structure. As the tests were made mostly

in producing wells, it is reasonable to infer that the point for which a rate of 62.14 feet per degree Fahrenheit was obtained is not far from edge water, and, in view of the relative effects of oil and salt water on the transmission of heat, it seems reasonable to expect that an equal increment will accrue as we pass from edge water to $a''c''$ at the base of the structure. Assuming such an increase, we have from Table IV for the sequence of reciprocal gradients at a'' c'', the values 82.8, 66.0, 63.5, 55.9, for the successive series of depths. These values are merely plausible estimates of the reciprocals of the mean gradients between domes and anticlines. The geometry of the isogeotherms (Fig. 1) leads one to suspect that the average depth-temperature curve in these areas approximates more closely to a straight line than is indicated by the preceding series of numbers.

Conclusive evidence on the diminution of temperature in the area immediately surrounding an oil dome was found by E.M. Hawtof (4) at Big Lake, Texas. He reports a rate of 111.2, on top of the dome; 137.9, on the north edge; 133.6, on the south edge; 133 on the west edge; and 148.2 feet per degree Fahrenheit at a point about 12 miles northwest of the dome. An important paper by Strong (5), just received, contains graphs showing a close correlation of the isogeothermal surfaces with the anticlines and synclines in some of the oil fields in Persia. Tests between domes and anticlines should be of great value in establishing the validity of the hypothesis of a variation of temperature with structure and it would enable us also to make a much more accurate estimate of an average gradient in sedimentary areas.

OTHER OBSERVATIONS

In Table V are tabulated the records from 25 non-flowing wells taken chiefly from the bulletin by N. H. Darton (1). The accuracy of many of these observations is probably questionable and the range of depths over which the temperatures have been taken are so irregular that it is difficult to properly interpret the averages with reference to the summaries contained in this paper. Excluding Lake Tahoe, for which the gradient is negative, an average value for 24 stations is 63.7 feet per degree Fahrenheit.

The reciprocal of the mean gradient determined from the records of 3,011 overflowing wells, contained chiefly in Darton's (1) bulletin, is 1°F. in 48.92 feet. Rejecting 164 observations for which the residual equals or exceeds 5*r*, the reciprocal of the mean gradient is 1°F. in 47.82 feet. No further rejections are indicated by the calculations. Rejection of 164 observations changed the value of the mean depth

TABLE V

TEMPERATURE GRADIENTS. OLD OBSERVATIONS

Town	*State*	*Range*	$b \times 10^5$	*Range Feet*	$b \times 10^5$	$1/b$	$b \times 10^5$
Phoenix	Arizona	—	—	100– 835	836	119.7	1,473
Prescott	Arizona	—	—	205–1,285	1,124	89.0	2,202
St. Augustine	Florida	170–1,110	606	170–1,340	919	108.8	1,142
Des Moines	Iowa	250–1,000	1,400	250–2,250	749	133.5	867
Belle Island	Louisiana	—	—	427– 975	1,269	78.8	1,179
Bay City	Michigan	—	—	1,304–3,455	1,535	65.2	1,427
Cheboygan	Michigan	100–2,000	810	100–2,700	861	116.1	1,085
Grayling	Michigan	500–2,150	2,301	500–2,600	2,222	45.0	2,023
Alma	Michigan	—	—	157–2,863	1,766	56.6	1,788
Keweenaw Point	Michigan	60–1,080	1,009	60–5,367	852	117.4	919
Freeda	Michigan	—	—	100– 950	952	105.0	1,505
Muskegon	Michigan	—	—	240–1,150	1,544	64.8	1,704
Port Huron	Michigan	—	—	300– 838	603	165.9	1,253
Lake Tahoe	Nevada	—	—	50–1,506	1,779*	56.1	2,656*
Tonopah	Nevada	—	—	100– 780	2,019	49.5	2,833
Tonopah	Nevada	—	—	317– 600	2,299	43.5	3,183
Tonopah	Nevada	—	—	100– 766	2,586	38.7	3,473
Virginia City	Nevada	—	—	1,482–2,128	2,542	39.3	3,289
Virginia City	Nevada	—	—	845–2,017	3,378	29.6	3,342
Isleta	New Mexico	—	—	443– 843	1,740	57.5	2,693
Findlay	Ohio	—	—	1,165–2,980	801	124.9	1,050
Plymouth	Ohio	—	—	1,400–3,000	1,363	73.4	1,390
Homewood	Pennsylvania	—	—	3,600–4,295	3,220	31.1	1,402
West Elizabeth	Pennsylvania	525–2,397	945	525–5,380	1,486	67.3	1,362
Mannington	West Virginia	100–1,000	956	100–2,500	996	100.4	1,044
A. Arithmetic mean. Formula 7		n	7		24		24
		b	.01147		.01569		.01818
		r	.00379		.00534		.00574
		r_0	.00143		.00109		.00117
		$1/b$	87.2		63.7		55.0
B. Weighted mean. Formula 8		m		2,162			
		b			.01579		.01587
		$1/b$			63.3		63.0
C. Arithmetic mean. Formula 7. $1/b \gtrless 40.49$ rejected		n			20		20
		b			.01297		.01606
		$1/b$			77.1		62.3

* Theoretically rejected observations.

of the wells from 445 to 400 feet. As it is hardly to be expected that reliable information can be obtained from wells of such shallow depths, no further consideration will be given these observations in this paper.

From DeGolyer's (6) observations in Tuxpam, Mexico, there results the following reciprocal gradients by using all of the observations, inclusive, between the indicated depths.

	Feet	*Feet per °F.*
Llano Grande	100–2,683	32.7
Tanhuijo	1,060–3,558	32.0
Tlacolula	75–4,026	42.6
Tlacolula	75–4,080	40.3

Roy O. Armstrong has kindly communicated to the writer the results of two tests in the oil fields of Canada. Averaging the observations by the usual least-square method, from a depth of 250 to 1,500 feet, inclusive, in a well located in Sec. 17, T. 19, R. 2W, 5th, Alberta, the resulting reciprocal gradient is 71.1 feet per degree Fahrenheit. From a well in the southern part of the field in Turner Valley, Alberta, the value 44.8 feet was obtained from a range of depths of 250 to 1,267 feet.

In marked contrast with these high temperatures in the oil fields of Mexico and Canada, we have the very interesting record of low temperatures obtained by Ralph H. Cleland (7) in the mining districts of Northern Ontario.

			Feet	*Feet per °F.*
Dome	Mine	Porcupine Dist.	248–3,065	164.0
Hollinger	"	"	235–3,892	223.4
McIntyre	"	"	181–3,865	233.2
Kirkland Lake	"	Kirkland Lake	2,490–4,905	130.7
Teck-Hughes	"	"	1,110–4,225	137.9
Lake Shore	"	"	391–3,575	167.1
Wright-Hargreaves	"	"	587–3,003	118.4
Sylvanite	"	"	495–2,993	142.2
Frood	"	Sudbury	400–3,100	155.2

The preceding averages were obtained by making least-square adjustments of all the observations recorded in each mine.

GENERAL CONSIDERATIONS

If our records represented true rock temperatures, it would be possible to draw tangents to the depth-temperature curves at desired depths. With smooth curves like those shown in Figure 2, it would be easy to make these determinations, and the results thus obtained would necessarily possess a physical significance not possessed by the successive straight lines used in this paper. However, imperfec-

tions in the present records preclude the possibility of using this method of evaluating the constants for very many of the curves.

Another method consists in computing the derivatives from a truncated power series that has been properly adjusted. In some of the fields, Salt Creek, for example, the depth-temperature curves possess a double curvature somewhat resembling a letter S. In these fields, the computation of the gradients from a truncated power series would lead to a misrepresentation of the facts.

Scientists use the term "normal gradient" without realizing, perhaps, that the term can be defined in a great number of different ways, and that some of the mathematical definitions can not be realized experimentally. The definitions in common use, equations 7 and 8, imply an average of a great number of gradients distributed uniformly or at random throughout a large area. This definition is theoretically correct but impossible of practical realization because of the very great number of observations required to determine an average that approaches a constant value. This is the method used by the Committee on Underground Temperatures of the British Association for the Advancement of Science in obtaining the commonly accepted value of 1°F. in 60 feet.

In the absence of complete evidence in the areas surrounding domes and anticlines, it is impossible to do other than to infer possibilities. About the only approach to a definite conclusion that can be made at present in regard to these areas is the possibility that the values of $1/b$ in Table II should be multiplied by factors which vary uniformly from a little more than unity for $1/b = 150$ feet per degree Fahrenheit to 3 or 4 times the tabular values as the lower limit of about 20 feet per degree Fahrenheit is reached. A closely related statement is the following: in oil-bearing areas, free from intrusives, the probability that a location is on a dome or the crest of an anticline increases from about 0.5 to practically a certainty (1.0) as the values of the reciprocal gradients decrease from about 50 to approximately 20 feet per degree Fahrenheit.

Koenigsberger (8) has grouped geothermal data for different geologic and topographic features into 10 groups and concludes that the averages for the different groups differ from one another—that for the bituminous group, particularly petroleum, being higher than the others, except for areas of recent intrusives.

Classification of the gradients in accordance with the sequence of geological epochs may provide a means of establishing a normal gradient for each epoch. The last gradient in the series would represent a normal gradient for an undisturbed earth.

An entirely different approach to the solution of the problem was proposed by the late G. K. Gilbert of the United States Geological Survey. In the first and third Year Books of the Carnegie Institution of Washington (1902 and 1904) he proposed the drilling of a deep well in plutonic rocks. The importance of this suggestion has been again emphasized by the recent observations of R. H. Cleland (7) in northern Ontario, Canada, which show that the reciprocal of the mean gradient in undisturbed areas of crystalline rocks may equal or exceed 200 feet per °F. (109.7 meters per °C.).

Jeffreys (9) estimates that subsidence to a depth of 10 kilometers during a geologic period of 130 million years causes a rise in temperature of about 250° C. at the plane of contact of the sediments and the crystalline rocks. As the heat of compression is less than 1° C., the rise in temperature is due almost entirely to the flow of radioactive heat into the sediments. With these facts in mind, let us consider the changes in the gradient at the surface of a sedimentary area. First, depression of isogeotherms immediately beneath ocean floors causes an increase in the flow of heat beneath oceans as compared with undisturbed land areas; and likewise, the sinking of the base of the sedimentary column into rocks of high temperature tends to increase the gradient during subsidence. Second, inasmuch as the total height of material eroded from a mountain range during the process of base leveling the range is several times the original height of the range (10), it follows that large quantities of heat in these areas are brought nearer to the surface of the earth by mass displacement. The net result of these activities is that in areas of sediments which have for one or more times been subject to uplift and subsidence, the total quantity of heat remaining in the rocks down to the level of concentric isogeotherms is probably at a minimum: the observed gradients at the surface, however, because of erosion and mass displacement outward in the vertical, are at a maximum. Thus, the absorption of heat during subsidence, and the subsequent erosion and displacement of rocks toward the surface, may account, in part, for the relatively high gradients found in sedimentary areas. Even thin sediments which are the remnants of extensive erosion, as at El Dorado, Kansas, may retain some of the absorbed heat. In undisturbed areas, however, the gradients are probably at a minimum and represent a normal gradient in the sense that such a gradient is the result of an undisturbed flow of heat that began immediately following the solidification of the crust. As suggested by J. S. De Lury (11), a normal gradient as thus defined may equal or exceed 200 feet per degree Fahrenheit. Observations at Grass Valley, California, Frank-

lin Furnace, New Jersey, and the upper peninsula, Michigan (Table I), tend to support this conclusion. Core-drill holes in areas of undisturbed igneous rocks would give us valuable information on this important question.

RECAPITULATION

In order to give a general idea of the areal distribution of gradients, the maximum and minimum reciprocal gradients have been tabulated in those areas in which there are a considerable number of observations. We have for the first 1,000 feet:

	Feet per °F.	*Meters per °C.*
Appalachian Mountains	68–131	37–72
Wyoming	19–74	10–41
Southern California	40–83	22–46
Louisiana	33–57	18–31
Kansas	46–82	25–45
Oklahoma	37–162	20–89
Texas	22–156	12–86
New Mexico	130–228	71–125

The well at Albany, Alabama, is not included in the preceding summary. The lowest temperatures are found in the Permian basin (12)—that is, southeastern New Mexico, western Kansas, western Oklahoma, and western Texas. The highest oil-field temperatures occur on the salt domes of the Gulf Coast, including northern Louisiana, and on structures of large closure in Wyoming.

The computed averages are as follows.

	Feet per °F.	*Meters per °C.*
Crests of 57 structures	49.8± 1.2	27.3±0.7
Flanks of 57 structures	62.1± 1.9	34.1±1.0
138 locations, including flanks of oil structures	65.2± 1.6	35.8±0.9
9 locations, excluding flanks of oil structures	108.0±10.6	59.3±5.8
4 locations in oil fields, Tuxpam, Mexico	36.3± 1.8	19.9±1.0
2 locations in oil fields, Alberta, Canada	52.5	28.8
9 mines, northern Ontario, Canada	156.0± 7.3	85.6±4.0

The preceding results, with the exception of the oil fields at Tuxpam and the mines in northern Ontario, are the averages for the first 1,000 feet.

From Table IV and the preceding tabulations, we have the following averages for the indicated successive ranges of depths.

	100 to 1,000 Feet	*100 to 2,000 Feet*	*100 to 3,000 Feet*	*100 to 4,000 Feet*
Crests of 57 structures	49.8	50.6	50.0	47.4
Flanks	62.1	57.3	56.0	51.3
138 locations, including flanks of oil structures	65.2	62.6	59.6	54.6
9 locations, excluding flanks of oil structures	108.0	101.0	95.7	—

On account of the rapid diminution of the number of wells with depth (Table IV) the accuracy of the preceding sequences of numbers diminishes rapidly as the depth increases.

No attempt has been made in this paper to extend an average depth-temperature curve beyond a depth of 4,000 feet. Such an extension probably involves the average thickness of the sediments and other factors that have not been investigated.

CONCLUSIONS

Practically nothing is known in regard to the positions of the isogeotherms over metalliferous deposits, such as are found in northern Ontario, Canada, and elsewhere throughout the world. As a result of ascending waters that have long since become extinct, it is reasonable to infer that the isogeotherms in many of these areas are depressed relative to those in the immediately surrounding zone. However, granting this possibility, it seems rather improbable that the reciprocal gradients in the extended zone surrounding these areas of very low temperatures should be less than 100 feet per °F. (54.9 meters per °C.); nor is it altogether improbable that the rate may not exceed 200 feet per °F. (109.7 meters per °C.).

Comparison of this low rate of 1° F. in 200 feet in the slightly disturbed rocks of the Canadian shield with the preceding rates (49.8, 62.1, 65.2) shows, as suggested on page 111, that there are at least two distinct types of normal gradient—one for sediments and one for exposed basement rocks that have remained static, or almost static, since their solidification.

Apart from differences in the thermal constants of the rocks and the variation of the annual mean temperature of the air with elevation, latitude, and geologic climate, the average of even a comparatively small number of gradients in the undisturbed crystalline rocks must be nearly constant over the surface of the earth.

In the sedimentary areas, however, uplift, subsidence, erosion, chemical reactions, and many other factors produce variations in the rock temperatures. Hence, a normal gradient determined from such areas depends on the number and distribution of the wells and the results of endless geological changes. For purposes of theoretical definition, the number of wells can be assumed to be so great that the average approaches a definite value, but, for practical purposes, it can not be assumed that the average obtained from a limited number of wells approaches a definite value. To illustrate, the reciprocal of the mean gradient, from 10 wells in western Texas is, say, 150; in Wyoming, again using 10 wells, the reciprocal is perhaps 40

feet per degree. The reciprocal of the mean of the corresponding gradients is 63.2, but, by varying the number of wells selected from the respective states, it is possible to obtain reciprocals of the mean gradient that vary from a little more than 40 to a little less than 150 feet per degree. This result suggests that the average for each geologic feature, the Permian Basin, for example, should be considered as a unit in determining the average. The distribution of these averages about a mean should be definitely related to the geological facts.

Summarizing the evidence, it appears that the normal gradient in the first 1,000 feet of sediments is probably greater than 65.2 feet per °F. (35.8 meters per °C.). The determination of an upper limit is not easily made. Assuming an arbitrary value of 82.8 as an average, and a minimum of 62.14, we have for the maximum reciprocal gradient, 103.5 feet. The mean from 9 locations exclusive of the oil fields is 108.0. It seems reasonable, therefore, to assume that the average of a large number of gradients covering the entire area of the United States, that is, the reciprocal of the normal gradient corrected for surface topography, is certainly greater than 60 feet per °F. (32.9 meters per °C.) and probably less than 110 feet per °F. (60.4 meters per °C.).

The wide interval between the preceding limits may seem unjustifiable, but when it is recalled that we have practically no observations in the large areas surrounding domes and anticlines, where the temperatures are presumably low, it is evident that a large element of uncertainty enters into our calculations. For depths exceeding 1,000 feet, the preceding numbers should probably be replaced by numbers of a lesser numerical magnitude. Existing observations do not give us very much information on this point.

The corresponding estimates for undisturbed basement rocks are: 100 feet per °F. (54.9 meters per °C.) for the minimum and probably not less than 200 feet per °F. (109.7 meters per °C.) for the maximum. These estimates are based on the data from northern Ontario, Canada (118.4 to 233.2).

In conclusion, it may be of interest to call attention to the fact that a value of the reciprocal of the normal gradient equal to 200 feet per °F. implies an age of a nonradioactive earth of 1,000 or 1,500 million years. Thermal data from undisturbed basement rocks would be of great value, therefore, in estimating the age of a nonradioactive earth, and incidentally, it would enable us, also, to estimate the amount of heat which is being supplied to the earth from radioactive sources.

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GEOLOGICAL NOTES

CUBAN JURASSIC[1]

INTRODUCTION

The San Cayetano and the Viñales formations exposed in the Organos Mountains in the Province of Pinar del Rio, Cuba, have been the subject of several articles published during recent years. The San Cayetano formation consists of a thick series of interbedded phyllites, quartzitic sandstones, and marbles, while the Viñales formation is composed almost entirely of dark gray-to-black, fairly thinly bedded limestones. Concerning the relationship between these two formations there has been considerable controversy owing to structural complications and to difficulty in finding contacts. By some geologists it has been contended that the San Cayetano formation lies unconformably below the Viñales limestones, the writers being of this opinion, while by others it has been asserted that the San Cayetano phyllites and quartzitic sandstones lie above the Viñales limestones. Practically all of the geologists who have interested themselves in this problem have followed Brown and O'Connell[2] in ascribing Jurassic age to the Viñales limestones and have attributed either pre-Jurassic or post-Jurassic age to the San Cayetano formation in accordance with their interpretation of stratigraphic relationships. The writers are not in accord with these age determinations and it is for the purpose of setting forth the observations upon which their opinion is based that this article is being published.

GENERAL DISCUSSION

Jurassic fossils have been collected from several localities in the Organos Mountains by various geologists. The best known localities are at Puerto del Ancon and at Mogote Mina Constancia, because they have been reported in publications. Less well known but equally as productive of well preserved fossils are areas at the east foot of Mogote de Guane; at the east foot of Sierra San Carlos about 2 kilometers north of the settlement of Punta de la Sierra; at the south

[1] Published by permission of the Atlantic Oil Company.

[2] B. Brown and M. O'Connell, "Correlation of the Jurassic Formations of Western Cuba," *Bull. Geol. Soc. America*, Vol. 33 (September 30, 1922), pp. 646–51.

foot of Sierra la Abra; at a point 1.5 miles southwest of La Jagua Vieja at a distance of about 100 meters east of the house of Sacario Otero; and at a point about 7 miles N. 20° E. from the town of Viñales near the house of Elpidio Diaz at La Jagua Vieja, on the trail between La Jagua and La Cañona. At this last locality such characteristic Jurassic ammonites as *Ataxioceras virgulatus* Quenstedt, *Perisphinctes cubanensis* O'Connel and *Perisphinctes plicatiloides* O'Connell have been found.

At all of these localities the Jurassic fossils occur in lenticular limestone or siltstone concretions. Inasmuch as most of these concretions have been found embedded in soil or on talus slopes bordering hills composed of Viñales limestones, it has been assumed by collectors that they originated in those limestones. Upon this basis the fossils collected from them have been accepted as determinative of the age of the Viñales formation. That they are not is the opinion of the writers. If they were, similar concretions should be found in place in the limestones of that formation, but where similar concretions are found in place, they occur in the phyllites of the San Cayetano formation, which crops out near the bases of the hills, below the slopes underlain with Viñales limestone. Fossiliferous concretions, containing Jurassic ammonites, have been found in San Cayetano phyllites at the east foot of Mogote de Guane; at a point about 1½ miles southwest of La Jagua Vieja, near the house of Sacario Otero; and at a point near the house of Elpidio Diaz, on the trail between La Jagua and La Jagua Vieja. From the evidence of these three localities the writers are of the opinion that the Jurassic ammonites collected from loose concretions on talus slopes in the Organos Mountains are weathered from the San Cayetano formation and not from the Viñales limestones, which the writers believe to be distinctly younger than the San Cayetano, and of post-Jurassic age.

In support of the opinion that the Viñales limestones are not of Jurassic age it should be noted that fossils have been found in them which are distinctly different from those found in the Jurassic concretions. At La Catalina, a settlement about 10 kilometers northwest of San Diego de los Baños, these limestones contain aptychi and ammonites that are considered of Lower Cretaceous age. Several miles northeast of La Catalina, on the trail between San Cristobal and El Rosario, two good fossil localities have yielded aptychi and ammonites that also have been determined as Lower Cretaceous in age. These fossils, in the opinion of the writers, establish with a reasonable degree of certainty that the Viñales limestones are of Lower Cretaceous instead of Upper Jurassic age and substantiate the

belief that the Jurassic fossils which have been reported from the Organos Mountains in the Province of Pinar del Rio, Cuba, came from the San Cayetano formation and not from the Viñales limestones.

CONCLUSIONS

From their study of the Organos Mountains the writers conclude that: (1) the Jurassic ammonites of Cuba occur in certain members of the San Cayetano formation and not in the Viñales limestones as has been reported; (2) the Viñales limestones are of Lower Cretaceous age; (3) the Viñales limestones lie unconformably above the San Cayetano formation.

The last conclusion is necessarily based upon a regional study, inasmuch as sharp contacts between the two formations are not found. That it is correct, however, is clearly demonstrated by great faunal differences, greater intensity of folding in the San Cayetano phyllites and quartzitic sandstones than prevails in the Viñales limestones, and a much greater degree of metamorphism in the San Cayetano formation.

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October, 1934

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REVIEWS AND NEW PUBLICATIONS

Geophysical Prospecting, 1934. Papers presented before the American Institute of Mining and Metallurgical Engineers (New York City, February, 1932, 1933, and 1934). 583 pp., many photographs and diagrams. Cloth. 6×9 inches. Price, $5.00.

This volume is the third of a series on geophysical prospecting, and submits the principal papers accepted by the Institute since early in the year 1932. It contains 16 papers on electrical methods, five on magnetic methods, five on seismic methods, one on geothermal measurements, and one on geophysics in the non-metallic field. There are no papers on gravimetric methods.

In the electrical methods group, eight papers deal with the presentation of data secured in the field and its interpretation in the terms of geologic structure. Five of these papers discuss the electrical determination of the attitude and position of sedimentary beds and hence are of particular interest to petroleum geologists and geophysicists. The other three present the solution of mining problems. Five of the papers in the electrical methods group present highly technical studies of the various theories of interpretation of resistivity data. All are of interest to petroleum geophysicists. The remaining two papers in the electrical methods group cover the Schlumberger methods of well surveying.

Five papers make up the magnetic methods group. Three of these papers deal with the application of the magnetic methods to mining problems. In two papers the detailed theory of two types of magnetic instruments is presented. These present data valuable to the petroleum geophysicists.

Of the five papers in the seismic methods group, two are devoted to methods and problems in reflection seismic prospecting, one to instrument problems in reflection seismology, one to refraction methods as applied to shallow overburdens, and one highly theoretical paper to an analysis of both refraction and reflection seismic profiles. The paper on instrument problems presents for the first time in the United States a discussion of the characteristics of instruments necessary for reflection seismic work. All of these seismic papers, whether or not the reader may agree with the conclusions reached, afford material of value to geologists and petroleum geophysicists working with the reflection method.

The two general papers present data of chief interest to mining engineers.

Many of these papers are of vital interest to petroleum geologists and geophysicists, and many of them will be of reference value. Most papers are presented by well known authorities in their particular field. Discussions which accompany most papers are ofttimes as valuable as the papers themselves. The book is gotten together in the customary high standard fashion of the A.I.M.M.E. and measures up in every respect to the previous geophysical publications of the Institute. It should be on every petroleum geophysicist's reference shelf.

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TULSA, OKLAHOMA
December 10, 1934

The Face of the Caspian Sea (Paleogeography of the Caspian during the Quaternary). By S. A. KOVALEVSKY. Published by Azneft, Baku, U.S.S.R. (1933). 129 pp., 22 maps and charts.

This excellent review includes the study of recent geological history of the Caspian Sea superimposed on the available history of the human race, the most ancient evidence of which dates back 3,400 years.

The author necessarily qualifies the book by stating that the historical limits and fluctuations of the Caspian are only approximations. A century is the usual limit of exactness. Further, even some distinct level, determined and attached to a well established point of the geographical element, can not be a general equivalent indicator for the whole sea, as during that period different parts of the Caspian and its basin have experienced epeirogenetic movements in various degrees. Nevertheless, generally it is necessary to apply the level indicators of different parts to the whole sea without particulars of the epeirogeny of the parts and the whole.

The fundamental theory is that the century movements of the earth's crust in the present area of the Caspian Sea during the time under study were very much weaker than in the central Russian part of its basin. This is founded on the view that the Caucasian slopes were less heavily laden, and much earlier freed from the weight of their inheritance of the Glacial age than the Russian north, and consequently the intensive isostatic fluctuations of the freeing of the Caspian blocks arrived at a relatively steady balance much earlier. Only the Kura depression and, in part, the Trans-Caspian depression of the lower reaches of the Uzvol, lying opposite it, could show positive movements in the historical period under consideration. Besides it is suspected that the cross belt of the Caucasus, from Azerbaidjan to the Stavropol shield of a negative compensatory movement, raised the Manich divide above the level of the ocean.

The development of the Caspian Sea of the present day in its historical stages is reviewed as follows.

More than 34 centuries before our day early records speak of "the Caspian—the Pool of Sun" of the Aegean sailors, the pirates, argonauts, whose daring raids and unintentional geographical discoveries are told in the songs of Homer and of successive poets. In those times the Straits of Manich still existed, through which the superfluous waters of the Caspian, then having an outlet, flowed to what was the Central sea for the Greeks, the Aegean. The Manich divide evidently had not yet risen above the level of geodetic zero, and the water in the straits flowed as a "deep and slowly flowing river." The Caspian then stretched along the ancient depression of the Volga far northwest, and there ended as a short canal something like Neva River, only much greater, feeding the sea from the "dead" waters of the Arctic basin (at that time the Baltic and Arctic seas were united). The latter was called Amalkhisky by the aborigines of the Baltic, and it is identified with the late phase of high water, the Ancillus Lake of geological history, left on the Hyperborean-Scythian north by the retreating ice. The "Dead waters" passing round the back of Europe, united with the Kroniysky sea and the Atlantic sea, which through the straits of the Pillars of Hercules, Gibraltar, carried its current into the Central sea.

As a heritage from that time, the heroic days of Greece, which in the geological chronology of the Caspian are identical with the end of its Khva-

linsk age, in the Caspian lowlands there have remained terraces and shore ridges of the "upper-ancient Caspian" age rising to the present level among deposits containing forms resembling the present *Didacna trigonoides* Pal.

Twenty-four centuries ago Hecataens of Miletus, the "much-travelled" geographer, does not mention the straits of Manich, though he keeps the uninterrupted water contour of Europe, in which the "Caspian or Hyrcanean" sea remains a bay of the northern Scythian ocean. It is probable that in the thousand years that had passed a divide had formed above the level of the sea at Manich, reducing the straits to a shallow passage and in the district of the basin feeding it, the Baltic, the Ancillus Lake, flowed into the Caspian

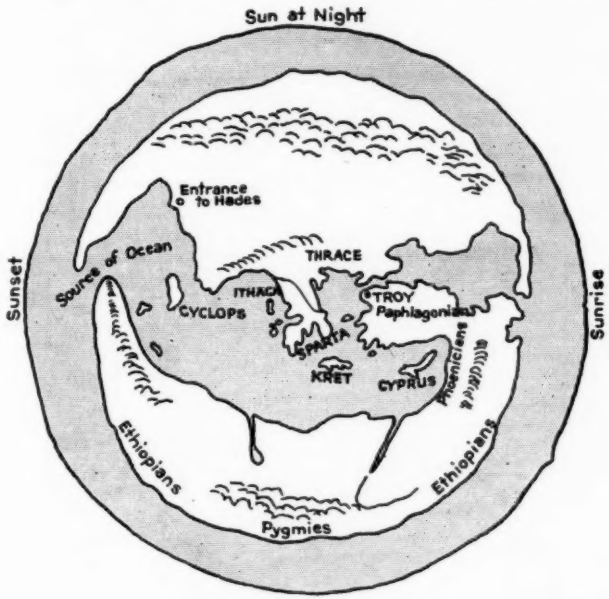

FIG. 1.—World after Homer.

with a weakening flood. With its waters the recent northern settlers migrated south. In the time of Hecataeus, the Manich divide raised the still abundant waters of the Caspian, flowing into the Pontus, slightly above the geodetic zero, in consequence of which terraces of that time could be deposited above the level of the ocean.

The last high terraces of the sea with decreased salinity, with *Adacna laeviuscula* Eichw. on the Baku side, and *Corbicula fluminalis* on the Aralo-Caspian, as well as the layers of the "Kemrud phase" of the Lower Volga district correspond with this stage of the history of the Caspian.

Half a century later—2,350 years ago—Herodotus visited Dnieper, Scythia, and Mesopotamia. Only the southern third of the Caspian Sea was

in sight of the "Father of History," who collected much material about Persia for his great work on the Graeco-Persian wars.

The southern third, measured by Herodotus in those days 2.5 times wider than it is now, overflowed toward the west and the east in the lower reaches of the Kura and Okhs, thus emphasizing the high level of the waters of the Caspian Sea, fed by the Ancillus waters. On the northwest of the sea, Manich was a scarcely noticeable canal called the "Cimmerian Ferry." The observed similarity of the contemporary fauna and flora of the Caspian Sea with that

FIG. 2.—Aralo-Caspian and other post-Pliocene basins.

of the Baltic and Arctic seas,—for example, seals and white fish, which at the same time are absent from the Black Sea,—indicates a very recent passage of these types, possibly through the Ancillus waters, and at the time Manich was already too shallow for migration.

Twenty-two and a half centuries before our time an enlightened adventurer-sailor from Marseilles—the Greek Pytheas—made a year's "fabulous" round-Europe voyage rich in geographical discoveries and observations: from Marseilles to the "Tin Islands," Great Britain, from there to the land

at the Arctic circle, "Thule," Seeland, then further to the edge of the northern ice and from there to the east round the northwestern frontiers of the continent of Europe. From the ocean, Pytheas penetrated, evidently by open water, to the amber-bearing shores of the "Scythian sea," Ancillus Baltic, having noticed in it at three days' sail from the Scythian shore "an island of enormous size," "Basilia" (otherwise called Baltzia), the present Scandinavia. And finally also evidently sailed through the abundant waters of the Caspian and Manich to the mouth of the "Tanais" and from there by the Mediterranean seas home to Marseilles. The Caspian of that time still kept its connection with the northern-feeding Ancillus basin of the Baltic, and partly with the western Black Sea, absorbing the small superfluity of waters of the Caspian not compensated by evaporation. The Manich divide and the level of the sea, it is supposed, reached a height of 20 meters above zero.

Twenty-two centuries ago the navy of Seleucus I on the Caspian under the command of the Macedonian Patroclus made a thorough investigation of the Caspian Sea. Patroclus established the mouth of the Oksa-Amu-Darya on the eastern side of the sea, and on the north of it the separate mouth of the Syr-Darya-Jaksart (?). On the north of the sea the Volga Strait is shown as being 1,000 kilometers long, that is, reaching to the present Nijni-Novgorod district. The Manich strait has turned into a marshy swamp, impassable for vessels, and Patroclus submits to his patron, the Babylonean satrap Seleucus I Nicator a project for deepening works for making a Manich canal. The Manich water-shed is supposed to have been 20 meters above zero, and at about the same height was the level of the Caspian Sea, closing up and ready for regression but still extending from Nijni-Novgorod to the Persian shores, and from Evlakh in the Transcaucasus to the Boyadag in the Trans-Caspia.

Twenty-one and a half centuries ago the learned Hellene, Eratosthenes, systematizes the geographical accumulations of antiquity, giving the geographical contributions of Pytheas and Patroclus their due, and praising very highly their work on the Caspian Sea. In the time of Eratosthenes the drying-up of the Caspian quickens and the level of its waters retreats from the Manich divide.

Twenty and a half centuries ago the famous historian Polybius declares that Manich is the chief line in the system of the Tanais, although at that time in the Don there was undoubtedly an abundance of water and Manich evidently already exists only as a bifurcation of the Volga, possibly flowing through the "canal of Patroclus," which in some unknown way has been made. A contemporary of Polybius, the traveller Eudoxus of Kisik, notes waterfalls on the Uzboi flowing into the sea whose level reaches the level of the ocean.

Twenty centuries before our time the historian Diodorus Sicilus repeats the evidently anachronistic statement of the early geographers that the Caspian is a bay of the Northern Ocean. According to all the signs the Caspian Sea had already lost its former connection with the Ancillus waters of the "Northern Ocean" with which it had been flooded.

Nineteen and a half centuries ago the last of the great geographer-travellers, Strabon, still speaks from former observations of the already non-existent connection of the Caspian Sea with the Northern Ocean, taking the remaining Volga Bay which covered the Kalmyk-Bukieff, now dry delta, for

the wide mouth of the ocean straits. At the same time the geographer, by the relation of the mouth of the river Kura with the Arax, and the Oxus with Okhus, which he notes, makes it possible to establish the fact that the level of the sea had fallen to 9 meters below the level of the ocean. In the channel of the Uzboi the shallow Okh-Tedjen has the chief significance, and the Ox-Amu discharges the greater part of its water into the Aral, and only a small stream into the Caspian through the Uzboi. Jaksart-Syr is out of sight but already evidently does not flow into the Caspian through the Chegan valley. The mollusc of the Littorin transgression—*Cardium rusticum* (*edule*)—emigrates through the black waters and old river courses of Manich, into the Caspian Sea, already more saline from the process of drying up, and its coming establishes the beginning of the Littorin age.

Nineteen centuries before our time the great naturalist Pliny and his fellow countrymen, Pomponius Mela and Curtius Rufus, note the presence in the Caspian of a dried-up Kalmyck-Bukeieff delta standing up out of the water and the existence along the Ergheny Lookomorye of a drying-up bay, Scythian bay, sometimes flooded with shallow water, sometimes turned into a marsh. Curtius Rufus notes the complete separation of the Caspian from the Northern Ocean. The sea-level sinks to 11–12 meters below zero. The Volga is at this period a shallow river with an estuary which was entirely bared to its bed by the water being blown off by the wind. The total amount of water emptied into the Caspian does not nearly compensate for the evaporation from the sea, the level of which continues to sink rapidly.

In the fourth century of the Christian era, about 16 centuries before our time, the Greek geographer, Agaphimer, states that the mouth of the Volga measured 4 stadia, equal to 650 meters, thus noting the comparatively small volume of water in the chief feeder of the Caspian. At this same time his fellow countryman, the writer of Latin history, Ammianus Marcelinus, does not note any flow on the Uzboi. The Caspian experiences a crisis in water-supply and dries up, quickly reducing its contours and level.

In the fifth century of the Christian era, Esdiger II builds the walls of Derbent, extending them to the retreating line of water. At this time walls were built to the shore in Hyrcania too.

In the sixth century work on the Derbent and Hyrcanian walls was renewed, extending them to the retreating sea-level. The shoals of the Baku archipelago—Makaroff (18–20 meters from sea-level), Ignatia (24–27 meters), and Polovachoff (26–30 meters)—little by little join on to the continent, and on them arise favorable conditions for settlement.

In the seventh century, the sea-level reaches its lowest—56 meters from the geodetic zero. The shoals of the Baku archipelago join on to the mainland and the marine belt is inhabited by a settled population. The bed of the Volga in the part near the sea sinks 5.8 meters below the oceanlevel.

The Derbent walls extend more than 6 kilometers from the present town, reaching the 5.5 meters-isobath but still not reaching the line of water. Khazars from the north force the Derbent passage which has been bared by the sea, and destroys the walls.

In the basin of the Volga the deepened valley completes the contemporary line of the Caspian, drawing into its system a quantity of important rivers separated from other systems with higher valleys.

In the eighth century, 12 centuries before our time, progress is reflected

on the earliest known copies of the maps of the great Alexandrian geographer of the second century, Claudius Ptolomeus. The Caspian has already lived through its crisis as a drying-up sea and under the influence of the new Volga, and not less stormily than before, changes its size and level, but this time increasing them. On the Ptolomeus map we find the sea at a level of 40 meters below the ocean level. Although on the eastern shore rivers are marked, in reality they belong to the independently existing Aral Sea, which had not yet entered the orbit of western geographical notions.

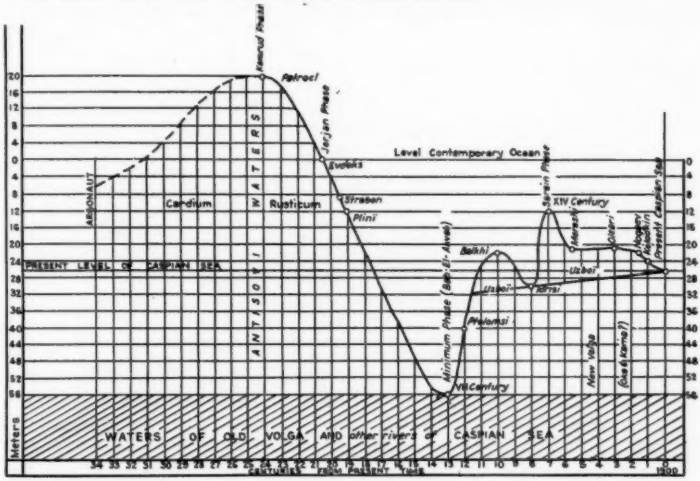

FIG. 3.—Diagram showing changes in level of Caspian Sea.

The fluctuations of the sea-level during the known historical period can be shown in graph form, as indicated on the accompanying chart (Fig. 3). On this curve of the oscillations of the sea-level of the Caspian from the 34th to the 13th century before our time the separate levels taken for the days of Patroclus, Eudoxus Strabo, Pliny, and the seventh century fit in the descending curve fairly consistently and thus seem to confirm the propriety of taking the composing elements in the steady process of lowering of the level.

The ascending curve, based on the data taken from the later writers, will be reviewed in a subsequent publication, according to Kovalevsky.

BASIL B. ZAVOICO

TULSA, OKLAHOMA,
December, 1934

"Geologische Studienreise in Nordamerikanischen Erdölfeldern" (Geological Field Trip Through North American Oil Fields). By A. BENTZ. *Petrol. Zeits.*, Vol. 30 (1934). Reprinted as a 43-page pamphlet, with 40 illustrations. Verlag für Fachliteratur, G. m. b. H., Wien 19, Vegagasse, Austria.

This paper will make an excellent text for American geologists and geological students who wish to improve their geological German and at the same

time desire an excellent elementary view of American oil fields. The paper presents data collected by Bentz on his visit to the oil fields at the time of the International Geological Congress, plus a careful digest from the literature. It comprises for each area brief statements of the general geology of the area, of the bibliography of important key literature, of the geology of one, two, or three characteristic and usually the most important oil fields in the area, and of drilling and production practice.

The foreign geologist who prefers German to English will find this paper has as excellent a resumé of American oil fields as there is available in English.

DONALD C. BARTON

HOUSTON, TEXAS
November 14, 1934

"Sobre a Bacia Sedimentaria Gondwanica na Republica do Uruguai" (On the Gondwana Sedimentary Basin of the Republic of Uruguay). By VICTOR E. OPPENHEIM. *Annaes da Academia Brasileira de Sciencias*, Tomo VI, No. 3 (Rio de Janeiro, Brazil, September 30, 1934).

While studying the geology of the southern states of Brazil, the author extended his studies to the sedimentary Gondwana basin of the Republic of Uruguay. He was able to determine the Uruguayan equivalents of the Brazilian formations of the Gondwana system and extend his geologic map to cover the greater part of this republic.

He also discovered for the first time that the sediments of the area of Carmen known as "Areniscas de Carmen" correspond stratigraphically and lithologically with "Arenito das Furnas" sandstones of the State of Paraná in Brazil, thus adding a new member to the Devonian formations of Uruguay, until now unknown.

The logs of a number of wells drilled in Uruguay were studied and several of the most characteristic are presented in the paper.

From the scope of geological and structural data obtained, the author concludes that there is very little probability of finding commerically exploitable petroleum in Uruguay.

The paper is completed by a geological sketch map of the Gondwana formations of Uruguay.

Angewandte Geophysik für Bergleute und Geologen, Zweiter Teil (Applied Geophysics for Miners and Geologists, Part II). By HERMANN REICH. 153 pp., 73 figs. Akad. Verlags. m.b.H., Leipzig (1934). Paper. Price, M.10.60.

This second, supplementary volume on applied geophysics by Reich will prove a valuable aid for those who are interested in the application of geophysical methods to mining. The book is written in an easily comprehensible, non-technical style.

There are four chapters and a short appendix. The physical properties of eruptive rocks, crystalline slates, and lodes are discussed in the first chapter. The second chapter deals with prospecting methods. Naturally, most of the space is devoted to magnetic and electrical methods. However, the seismic and gravimetric methods are described briefly. Some results of investigations are given in the third chapter. Prospecting for non-metallic rocks and for

water, the use of geophysical methods in the investigation of building and dam sites, in the location of caves, and in treasure hunting are discussed in the last chapter. Reflection shooting, Mueller's electro-chemical method, and Laubmeyer's prospecting method by the analysis of soil gases for hydrocarbons are briefly described in the appendix.

This volume furnishes interesting reading. In the reviewer's opinion, refraction shooting is superior to electrical conductivity methods as far as the accuracy of depth determinations is concerned; the author (p. 55) seems to consider the electrical methods as accurate as refraction shooting. The substitution of I for J in names, for instance I. N. Hummel for J. N. Hummel, is misleading.

The author's comment (p. 146) on new geophysical methods is interesting and should be properly impressed on many scientists and most company executives who are frequently approached by "inventors" of geophysical methods and devices.

Reports about geophysical methods with absolutely fantastic possibilities appear frequently. They are commented upon accordingly by the daily press, which reports unparalleled successes. The greatest reserve and scepticism regarding all such news is in order. Up to the present time no method which was announced with grand ballyhoo has been able to stand serious examination. Also, one should not be influenced by the purportedly expert testimony of well known scientists. Applied geophysics is a typical border field. Geologists are not as a rule capable of judging and comprehending the physical possibilities and assumptions; physicists do not generally know the limits imposed by geology and mining. Thus it often happens that an actually worthless method is recommended by serious-minded scientists. Only an unprejudiced critical examination by experts from *both* of the great fields of knowledge can furnish a decision regarding the value or worthlessness of such a method.

L. W. BLAU

HOUSTON, TEXAS
November 30, 1934

"Engineering Studies and Results of Acid Treatment of Wells, Zwolle Oil Field, Sabine Parish, Louisiana." by R. E. HEITHECKER. *U.S. Bur. Mines Rept. Investigations 3251* (1934). Mimeograph, 35 pp., 13 tables, 14 figs. Size, 8×10½ inches. Paper.

In this paper of 35 pages, with several tables and diagrams, Heithecker has brought together practically all the statistical information relative to the Zwolle oil field, and the use of acid there, with conclusions based on conditions disclosed by this study.

The first part of the report, entitled "Engineering Studies," takes up the stratigraphy of the area, with development history, reservoir conditions, factors relating to production, and inferences therefrom.

Included in the second part, "Acid Treatment of Wells in the Zwolle Field," are statements of methods used, with results, and illustrative examples of effects produced in individual wells.

The oil at Zwolle is found in a marl zone equivalent to the Saratoga chalk, locally found at the top of the Upper Cretaceous, and in the Marlbrook-Annona chalk section below it. These formations have an irregular porosity not natural to them, doubtless due to fractures and solution channels. Several theories have been advanced to account for the presence of oil in these beds, and its behavior there. Evidence which is practically conclusive is presented that the oil and water both have migrated upward from the sandy Ozan below the chalk.

The use of acid in oil wells is of course a comparatively new procedure, and one particularly adaptable to this type of reservoir. A period of 13 months is dealt with, and 113 wells with 134 treatments were available for study out of about 150 wells treated.

Interesting new practices are involved in this work, such as shipping the hydrochloric acid in rubber-lined tank-cars at 30 per cent strength and of 19.2° B. (1.1526 specific gravity), and diluting it to 15 per cent strength at the well (1.07 specific gravity); also the use of an inhibitor to prevent corrosion of iron equipment while allowing limestone to be attacked, a very clever answer to a chemical conundrum. It is estimated that the usual amount of acid used, 1,000 gallons, will dissolve 11 cubic feet of limestone in the Zwolle district. Only about 40 per cent of the wells were productive before the use of acid, and in these 13 months with acid, 47.2 per cent produced.

Emphasis is properly placed on the uncertain nature of the results of acid treatment. Wells have been brought in as producers which made little or no oil on first completion. On the other hand, about 45 per cent have not been improved by the use of acid.

The overall results are shown by a curve giving the estimated normal decline and the actual production, the difference indicating an increase of 604,000 barrels due to acid treatment. As the treatment of 150 wells would cost around $45,000, it is clear that, with oil at $1.00 per barrel, the increase in gross income may be taken as $559,000.

In deciding whether or not to use acid, the owner is staking a comparatively small amount on the chance of a large return, some of the wells having produced enough after treatment to look very important to a small producer. The results obtained have undoubtedly kept drilling operations going on, whereas they probably would have ceased entirely some time ago.

Many matters are included in this report not mentioned in this brief review, and all those interested should secure it, as both the subject and the treatment make it a welcome addition to Louisiana literature. A forthcoming paper will discuss the geology of the same area.

H. N. SPOFFORD
Geologist and engineer

3427 BEVERLY PLACE
SHREVEPORT, LOUISIANA
December 10, 1934

"A Study of the Sediments of the North Baltic and Adjoining Seas." By STINA GRIPENBERG. *Geographical Society of Finland*, Fennia 60, No. 3 (1934), pp. 1–231, tables 1–28, figs. 1–45.

This report, representing 10 years' study by Miss Gripenberg, has recently appeared. As it contains a wealth of information, it should be brought to the attention of American students of sedimentation. One of its most important contributions is its detailed account of the methods of studying sediments. The main subjects considered in the paper are: (1) mechanical analysis of the sediments, especially methods of dispersing the constituents and means of presenting results of the analyses; (2) organic content of the sediments, particularly the nitrogen and carbon content; and (3) calcium carbonate content of the sediments, with special reference to the conditions governing its accumulation in sediments. One of the most important features

the author points out is the effect of electrolites on the dispersal of the constituent particles during the process of making a mechanical analysis of fine-grained sediments. She presents data to show that unless the electrolites are removed, the particles tend to aggregate and the resulting analyses are apt to indicate that the sediments are two to eight times coarser than they really are. The paper contains a good bibliography, particularly of recent European articles on methods of studying sediments.

PARKER D. TRASK

WASHINGTON, D.C.
December 10, 1934

RECENT PUBLICATIONS

ARIZONA

"An Investigation of the Light-Colored, Cross-Bedded Sandstones of Canyon de Chelly, Arizona," by Edwin D. McKee. *Amer. Jour. Sci.* (New Haven, Connecticut), Vol. 28, No. 165, Ser. 5 (September, 1934), pp. 219–33; 9 figs.

BRAZIL

"Nota sobre o silex (chert) no sul do Brasil" (Note on Silex (Chert) in the South of Brazil), by Victor Oppenheim. *Annaes da Acad. Brasileira de Sciencias*, Tomo VI, No. 2 (Rio de Janeiro, June 30, 1934), pp. 83–87; 1 fig., 6 photos.

Mapa Geologico do Brasil Meridional (Map of the Geology of Southern Brazil with Special Reference to the Gondwana Formations), compiled by Victor Oppenheim. Serviço de Fomento da Produção Mineral, Buenos Aires, Brasil (1934). 2 sheets in colors, each about 35×18 inches. Scale, 1:2,750,000. Limited number of copies obtainable from the director of the Mineral Survey at Buenos Aires. Text to accompany map, in preparation.

CALIFORNIA

"Kettleman North Dome and Kettleman Middle Dome Fields—Progress in Development," by H. V. Dodd and Edward J. Kaplow. *California Oil Fields* (San Francisco, 1934), Vol. 18, No. 4 (April, May, June, 1933), pp. 5–20; 2 pls.

CHINA

"Geologie des Gebietes zwischen Yünnanfu und dem Yangtse-Kiang, Nord-Yünnan, China" (Geology of the Region between Yünnanfu and the Yangtse-Kiang, North Yünnan, China), by Karl Krejci. *Geol. Rundschau*, Vol. 25, No. 5 (Berlin, 1934), pp. 305–12; 4 figs., 1 table.

EASTERN MEDITERRANEAN

"Premiéres recherches sur les hydrocarbures minéraux dans les états du Levant sous mandat Français" (First Exploration for Hydrocarbons in the Countries of the Levant under French Mandate), by M. L. Dubertret. *Ann. Combus. Liquides*, No. 5 (Paris, September-October, 1934), pp. 877–99; 6 figs., 4 pls.

ENGLAND

"A Synopsis of the Jurassic Rocks of Yorkshire," by Vernon Wilson, J. E. Hemingway, and Maurice Black. *Proc. Geologists' Association* (London), Vol. 45, Pt. 3 (1934), pp. 248–90; Figs. 33–35; Pls. 16–18.

GENERAL

"Une nouvelle méthode pour déterminer la porositié des roches des séries pétroli et gazi-féres" (A New Method for Determination of Porosity of Oil- and Gas-Bearing Rocks), by O. V. Wyszynski. *Service Geol. Karpatique Biul. 23* (Warsaw, 1934). 32 pp., 1 fig. In Polish and French.

"Sulle corelazione stratigrafiche mediante il metodo dei residui insolubili" (Stratigraphic Correlation by Insoluble Residues), by Ramiro Fabiani. *Inst. Geol. R. Universitè* (Palermo, 1934). 7 pp.

"Nel paese del petrolio e dello Zolfo" (Petroleum and Sulphur), by Ramiro Fabiani. *Revista L'Universo*, Vol. 15, No. 8 (Palermo, August, 1934), pp. 647–75, 21 figs. Beautifully illustrated account of the author's trip with the excursion of the 16th International Geological Congress in the United States, July, 1933.

"Bemerkungen zu Trask's Methode der Bestimmung des organischen Gehaltes meerischer Sedimente" (Remarks on Trask's Method of Determining the Organic Content of Marine Sediments), by F. Hecht. *Senckenbergiana* (Frankfurt a. M.), Vol. 16, No. 1 (May 24, 1934), pp. 21–24.

"Our Present Attitude Toward Coring Devices," by Stanley Herold. *California Petroleum World* (Los Angeles), Vol. 27, No. 16 (November 8, 1934), pp. 16–18; 4 figs.

Annual Report for 1933–1934. National Research Council Div. Geol. and Geography (Washington, D.C.). By W. H. Twenhofel, Chairman of the Division, and 22 chairmen of committees. 228 pp., multigraphed.

"Report of the Committee on the Measurement of Geologic Time," by Alfred C. Lane, chairman. *Natl. Research Council Div. of Geol. and Geogr.* 86 pp., multigraphed.

"Correlation Chart of Geologic Formations of North America," by Hervey W. Shimer. *Bull. Geol. Soc. America* (Washington, D.C.), Vol. 45, No. 5 (October 31, 1934), pp. 909–36; 5 charts.

"The Structure of the Pacific Basin," by L. J. Chubb. *Geological Magazine* (London), Vol. 71, No. 841 (July, 1934), pp. 289–302; 4 figs.

GEOPHYSICS

"Gravity Measurements in the Great Hungarian Plain," by H. de Boeckh. *Jour. Inst. Petrol. Tech.* (London), Vol. 20, No. 131 (September, 1934), pp. 884–90; 3 figs.

"Auto Radio—An Aid in Geologic Mapping," by Ernst Cloos. *Amer. Jour. Sci.* (New Haven, Connecticut), Vol. 28, No. 166, Ser. 5 (October, 1934), pp. 255–68; 2 figs.

IDAHO

"Correlation and Interpretation of Paleozoic Stratigraphy in South-Central Idaho," by Clyde P. Ross. *Bull. Geol. Soc. America* (Washington, D. C.), Vol. 45, No. 5 (October 31, 1934), pp. 937–1000; 2 figs.

LOUISIANA

"Analyses of Crude Oils from Some Fields of Southern Louisiana," by A. J. Kraemer and E. L. Garton. *U. S. Bur. Mines Rept. Investig. 3253* (November, 1934). 36 mimeog. pp.

MEXICO

"Mitteloligozän in der Umgebung von Tampico, Mexico" (Middle Oligocene in the Region of Tampico, Mexico), by Hans E. Thalmann. *Geol. Rundschau*, Vol. 25, No. 5 (Berlin, 1934), pp. 325–29.

POLAND

"La faune de l'avant-pays des Karpates dans les environs de Stryj et de Dolina et sa signification pour la stratigraphie" (The Fauna of the Foreland of the Carpathians in the Vicinity of Stryj and Dolina and Its Stratigraphic Significance), by Boleslaw Böhm. *Service Geol. Karpatique Biul 21* (Warsaw, 1934). 50 pp., 2 pls., 2 figs.

ROUMANIA

"Sur les anomalies de gravitation constatées à Floresti (Prahava) et dans les environs" (Gravitational Anomalies at Floresti and Environs), by I. Gavăt. *Anuarul Institutului Geologic al României* (Bucarest, 1934), Vol. 16 (1931), pp. 683–706; 4 figs., 2 pls.

RUSSIA

"Oil Field Waters," by C. L. Maljarov. *Trans. Oil Geological Institute*, Ser. A, Vol. 46 (Moscow, 1934). 127 pp., 12 figs., 57 tables. In Russian.

"The Brachiopoda of the Bryozoa Limestones of the Kolwa River Region (Northern Ural). Pt. 1. Strophomenacea," by D. L. Stepanav. *Trans. Oil Geol. Inst.*, Ser. A, Vol. 37, No. 3 (Moscow, 1934). 63 pp., 4 pls. In Russian.

"Materials on the Tectonics of Northeast Asia," by S. V. Obruchev. *Problems of Soviet Geology* (Moscow), Vol. 2, No. 6 (June, 1934), pp. 182–200; 1 fig.; Vol. 2, No. 7 (July, 1934), pp. 1–16; 3 figs. In Russian. Bibliography of 61 titles, of which 17 are English and 5 are German. Author gives first scheme of geological structure of Northeast Asia, distinguishing an old platform as well as Paleozoic and Mesozoic folded zones and Tertiary areas of Pacific type.

"Oil Districts of Middle Asia," by S. A. Kovalevsky. *Azerbaidjan Oil Industry* (Baku), Vol. 150, No. 6 (June, 1934), pp. 52–57; 1 map, 6 photos. In Russian.

SIBERIA

"Das Pamir System—auf Grund neuerer Literatur" (The Pamir System —from Recent Literature), by Kurt Gundlach. *Geol. Rundschau*, Vol. 25, No. 5 (Berlin, 1934), pp. 330–55; 2 figs. Tectonics and stratigraphy of Pamir, the "Roof of the World," the region bordered by Turkey, Siberia, China, and India.

TRINIDAD

"Straight-Hole Technique in Trinidad and Its Effect on Well Spacing," by H. C. B. Hickling. *Jour. Inst. Petrol. Tech.* (London), Vol. 20, No. 132 (October, 1934), pp. 936–50; 1 fig.

"Some Considerations Affecting the Spacing of Oilwells (with Special Reference to Trinidad)," by M. A. ap Rhys Pryce. *Jour. Inst. Petrol. Tech.*, Vol. 20, No. 132, pp. 951–72.

WYOMING

"Stratigraphy and Paleontology of a New Devonian Formation at Beartooth Butte, Wyoming," by Erling Dorf. *Jour. Geol.* (Chicago), Vol. 42, No. 7 (October–November, 1934), pp. 720–37; 7 figs.

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 19, NO. 1 (JANUARY, 1935), PP. 132-141

THE ASSOCIATION ROUND TABLE

MEMBERSHIP APPLICATIONS APPROVED FOR PUBLICATION

The executive committee has approved for publication the names of the following candidates for membership in the Association. This does not constitute an election, but places the names before the membership at large. If any member has information bearing on the qualifications of these nominees, he should send it promptly to J. P. D. Hull, business manager, Box 1852, Tulsa, Oklahoma. (Names of sponsors are placed beneath the name of each nominee.)

FOR ACTIVE MEMBERSHIP

Raymond Miller Larsen, Thermopolis, Wyo.
C. E. Dobbin, Charles E. Erdmann, W. H. Emmons

John Charles Miller, Washington, D.C.
C. E. Dobbin, W. B. Lang, Hugh D. Miser

Ramiro Fabiani, Palermo, Italy
Arnaldo Belluigi, Stanislas Zuber, W. E. Wrather

FOR ASSOCIATE MEMBERSHIP

Andrew C. Elliott, Houston, Tex.
B. Coleman Renick, John R. Sandidge, John T. Lonsdale

Raymond Douglas Woods
Fred M. Bullard, F. L. Whitney, F. B. Plummer

PAPERS SUBMITTED FOR ANNUAL MEETING

The following is a preliminary list of papers for the twentieth annual meeting of the Association at Wichita, Kansas, March 21–23, 1935.

Leo Fortier, "McPherson-Voshell-Burrton Trend in Kansas."
T. C. Hiestand, "Regional Problems of Structure and Stratigraphy in Oklahoma and Kansas."
J. Brian Eby, "Relation of Geophysics to Salt Domes in Gulf Coast."
George Norton, "Upper Wellington and Lower Red-Bed Section in Kansas."
E. B. Noble and W. D. Kleinpell, "Geology of Edison Oil Field, California."
D. C. Barton, "Distribution of Crude Oil at Spindletop—A Study in Migration."
Edward Koester, "Geology of Central Kansas Uplift."
John Garlough and Garvin Taylor, "Hugoton Gas Field, Kansas."

TWENTIETH ANNUAL MEETING, WICHITA, MARCH 21–23, 1935

The executive committee has accepted the cordial invitation of the Kansas Geological Society to hold the twentieth annual meeting of the Association at Wichita, Kansas, Thursday, Friday, and Saturday, March 21, 22, and 23, 1935. The Allis Hotel, the convention headquarters, is admirably arranged for handling the Association registration, technical program, scientific exhibits, and other needs of the meeting. Other hotels are conveniently located to accommodate the usual large attendance. Reduced railroad rates are being arranged.

The technical divisions of the Association, the Society of Economic Paleontologists and Mineralogists and the Society of Petroleum Geophysicists, will hold concurrent annual meetings.

The Wichita committee on arrangements, E. C. Moncrief, chairman, Derby Oil Company, Box 1030, Wichita, Kansas, together with president Heroy, past-president Clark, and business manager Hull, met at Wichita, November 23, and outlined the work of each sub-committee. It is planned to have all regions and sections represented on the technical program and to allow ample time for discussion of the papers selected for oral delivery.

Field trips will be offered, particularly to the Lyons salt mine. Proper provision is being blue-printed for golfers, dancers, diners, talkers, listeners, and other special actors and auditors.

More details will be announced in the *Bulletin* and by mail.

The Wichita committees are as follows.

General.—E. C. Moncrief, chairman, Box 1030; F. L. Aurin, E. L. Bradley, John L. Garlough.

Registration.—Marvin Lee, chairman, 800 Bitting Building; R. A. Whortan, A. M. Meyer, E. Gail Carpenter, Roy H. Hall.

Entertainment.—Howard S. Bryant, chairman, 510 Ellis Singleton Building; E. A. Wyman, Lee H. Cornell, Jas. I. Daniels, C. J. Stafford, Walter W. Larsh.

Ladies entertainment.—Walter W. Larsh, chairman, 413 First National Bank Building.

Reception.—E. P. Philbrick, chairman, Box 1882; L. C. Morgan, W. B. Sinclair, Phil K. Cochran.

Publicity.—L. R. Fortier, chairman, 715 Union National Bank Building; L. A. Crum, Edward A. Koester.

Program.—W. A. Ver Wiebe, chairman, University of Wichita; J. F. Kinkel, F. E. Wimbish, Jerry E. Upp, Anthony Folger.

Equipment.—J. P. McKee, chairman, Box 1801; Glen C. Woolley, W. R. Vickery.

Trips.—L. W. Kesler, chairman, 527 First National Bank Building; Wm. L. Ainsworth, Garvin L. Taylor.

Golf.—Edwin N. Carlson, chairman, Box 521; Edwin A. Dawson, L. I. Yeager.

It is requested that titles, abstracts, and, in so far as available, complete manuscripts be sent as soon as ready to Professor Walter A. Ver Wiebe, Department of Geology, University of Wichita, Wichita, Kansas. These should be prepared in double-spaced typewritten sheets in duplicate, the

complete manuscript preferably in triplicate, in order to facilitate preparation of discussion. Titles and abstracts should be received by Professor Ver Wiebe before February 15, and, to be included in the printed program, must be received before March 1.

Paleontology titles, abstracts, and manuscripts are to be sent to Professor Gayle Scott, Texas Christian University, Fort Worth, Texas.

Geophysics titles, abstracts, and manuscripts are to be sent to Dr. B. B. Weatherby, Drawer 2040, Tulsa, Oklahoma.

PACIFIC SECTION ELEVENTH ANNUAL MEETING

The eleventh annual meeting of the Pacific Section, held at the Mayfair Hotel, Los Angeles, California, November 8 and 9, established a new high record for attendance at the Association's oldest and largest regional section. The two-day convention drew a total registration of 250. A. A. Curtice, president of the section, presided at a program of 14 papers of pleasing variety arranged by Harold W. Hoots, chairman of the program committee. William B. Heroy, of New York, president of the Association, attended and enthusiastically encouraged the Section with his presentation of conditions in the Association and the profession.

The Pacific Section of the Society of Economic Paleontologists and Mineralogists also held a business and technical session on the first day and evening of the annual meeting. A. R. May was chairman of the program.

Morning and afternoon sessions of the meeting were held in Rainbow Isle on the second floor of the Mayfair, both Thursday and Friday. Luncheons were served on the mezzanine. The Thursday evening session was held on the mezzanine. The dinner-dance on Friday night in Rainbow Isle served as a delightful closing event of the convention.

The business session, Friday afternoon, outlined important projects for the coming year, especially the plan to prepare a book covering the geology of the oil and gas fields of California to be published by the Association. This book should be a reference of inestimable value to the petroleum industry of California as well as to geologists throughout the world.

New officers elected by the Pacific Section are: Harold W. Hoots, of the Union Oil Company, president, succeeding A. A. Curtice; and Graham B. Moody, Box 1390, Station C, Los Angeles, secretary-treasurer, succeeding W. D. Rankin.

HAROLD W. HOOTS
President, Pacific Section

ABSTRACTS OF PACIFIC SECTION PAPERS

The papers and abstracts are numbered as on the printed program of the Pacific Section meeting, November 8 and 9, 1934.

1. E. B. NOBLE and W. D. KLEINPELL, The Geology of the Edison Oil Field (abstract).

The field is in an early stage of development, but there is sufficient data to suggest that the oil accumulation is due mainly to the thinning out of beds up the dip. Production at the present time is obtained from two zones, one of heavy oil from the Kern River and another of lighter oil from the Middle

and Lower Miocene. No production has as yet been obtained in this field from the Upper Miocene (Santa Margarita).

2. KENNETH L. GOW, The Geology of the Mountain View Oil Field (abstract).

This field, 4 miles southeast of Bakersfield, was discovered in 1930 and again in 1933. Production is obtained in the lower Kern River or Chanac and Santa Margarita formations. Structurally the field is a faulted monocline. It is 5 miles long and still growing both to the northwest and southeast. It averages 1/4 mile in width, and will probably be 1/2 mile wide when fully developed.

3. CHESTER STOCK, The Vertebrate Paleontology of the Sespe Formation (abstract).

The three principal areas from which vertebrate faunas have been obtained in the Sespe are north of the Simi Valley, Las Posas Hills, and South Mountain, California. At least four stages in the history of North American mammal life are known from the Sespe and these range in age from Upper Eocene to Lower Miocene. Their correlatives in the Cordilleran, Great Basin, and Great Plains provinces appear to be (1) Uinta, (2) post-Uinta or pre-White River, (3) Upper White River, and (4) Upper John Day or Lower Rosebud.

4. WAYNE GALLIHER, The Origin of Glauconite (abstract).

Describes how glauconite forms from biotite in Monterey Bay, California.

5. J. O. NOMLAND, A Trip Across Arabia (abstract).

In 1933, while doing geological reconnaissance at Hofuf on the Persian Gulf side of Arabia, it became necessary to cross by land to Jeddah on the Red Sea. A special permission was required from Ibn Saud, King of Arabia. This has been granted only a very few times earlier to Europeans or Americans. Three days were spent at Riyadh, the capitol, in the central part of Arabia, as guest of the King and his Ministers.

6. PARKER D. TRASK, The Organic Content of Some Tertiary Formations in California (abstract).

A paper bearing directly on the origin of petroleum.

7. OLAF P. JENKINS, Progress of the State Geologic Map of California (abstract).

Through funds of the Public Works Administration, placed in the hands of the United States Geological Survey, with a time limit up on June 16, 1935, a complete revision of the compilation of the map is under way. The work is being done under the direction of the chief geologist of the California State Division of Mines. Many areas in the state still need revision or are blank as regards reliable geological information.

8. HUBERT G. SCHENCK, The Oligocene Problem (abstract).

This preliminary report is based upon field and museum investigations in western Europe from August, 1933, to August, 1934. That there are strata situated between beds of late Eocene and early Miocene ages cannot be denied, nor is there any doubt of the succession of the Tongrian, Rupelian, and Chattian stages. Misconceptions regarding the Oligocene are due to incomplete data on the vertical ranges of certain fossils, redefinitions of terms without reinvestigations, changes of facies, and imperfect taxonomic studies. The Aquitanian stage of southern France may well be treated as Upper Oligocene rather than Lower Miocene, and the hypothesis that it is synchronous with the Chattian stage of Germany needs serious consideration.

9. GRAHAM B. MOODY, The Geology of Santa Rosa Island (abstract).

Thick sections of Eocene and Miocene sedimentary rocks are exposed on Santa Rosa Island. Faulting has influenced structural development to a large extent. Slickensides check the conclusion that horizontal movement has been greater than vertical along the principal faults. Greatest displacement is apparent along the Santa Rosa fault, which splits the Island into north and south parts. Eocene sedimentary rocks are exposed over large areas south of this fault but do not outcrop north of it. Interesting structures are the Hoya Vieja, Pedregosa, Cerro Pablo, and Arlington anticlines; the Pedregosa, Santa Rosa, and Beecher's Bay synclines.

10. R. D. REED and J. S. HOLLISTER, Geology of the Transverse Ranges (abstract).

Recent structural and stratigraphic work in the less known parts of the western Transverse Ranges throws some light on several problems of interest to California geologists. A few of these problems will be mentioned during the exhibition of a series of new maps, geologic, structural, and paleogeographic, and a few sketch structure sections.

11. ROBERT M. KLEINPELL, Discussion of Miocene History and Faunas (abstract).

Relative distribution of facies in the various Miocene foraminifer faunas of California is summarized and wherever possible compared with associated geologic phenomena such as lithologic facies, relative geographic distribution, observable structural features, and extra-foraminiferal faunal data. On the basis of the time relations of the associated phenomena summarized, the Miocene of California is classified into three separate geologic units of two distinct types, each unit having minor subdivisions of varying type and order of magnitude. Anomalies and similarities with the recorded Miocene history of Europe are briefly discussed.

12. ROBERT BALK, Comparison between the Structure of Intrusive Igneous Domes and Oil Domes (abstract).

The structures of many oil domes as well as those of several intrusive masses have been caused by deforming forces at least one component of which was directed vertically upward. The up-warped beds of oil domes have a counterpart in domal or anticlinal flow structures seen in intrusives. Associated with them are fracture systems which, in intrusive areas, appear in systematic angular relation to the older flow structures. One of these systems represents funnel planes, converging toward a zone below the structural apex. Measured offsets along these planes (normal faults) show that they serve to widen the expanding structures. Faults of the same nature have been recognized in oil domes of Wyoming, California, Montana, and other districts. In elongate domes transverse and longitudinal fracture systems can be distinguished. Under favorable circumstances, they may serve as conduits of oil or gas, on the one hand, or as planes of dike invasion and subsequent mineralization, on the other. There is reason to believe that detailed studies in fracture mechanics will permit predictions as to where maxima of distension are to be sought in domes. It may be possible, also, to determine maxima of uplift in complexly faulted areas, by means of careful observations of the details in subordinate faults, and where intrusive masses are present, they will perhaps aid and supplement the evidence by the configuration of their own structures.

13. L. M. CLARK and ALEX CLARK, The Vaqueros in the Temblor Range (abstract).

Vaqueros fossils, including *Ostrea vaquerosensis* and *Pecten magnolia*, have recently been found at several localities in a sandstone member occurring in the upper part of the Santos shale. This sandstone member, here referred to as the "Agua sandstone," is traceable from the vicinity of Carneros Creek to the mouth of Cedar Canyon, several miles farther northwest, and, in places, reaches a thickness of more than 300 feet.

Although evidence from other regions had previously suggested it, this discovery proves the Vaqueros age of at least the lower two-thirds of the Santos shale and necessitates its removal from the Temblor. As a result, the present known extent of the Vaqueros sea in the San Joaquin Valley has been considerably increased.

1. (Paleontology session). HUBERT G. SCHENCK, What is the Vaqueros Formation of California and is it Oligocene? (abstract).

The Vaqueros formation of California has never been adequately defined as a stratigraphic unit and its Miocene age is based upon assumptions. At least a part of this formation, as mapped by some geologists, is Oligocene, if reliance be placed upon data as reliable as those upon which its Miocene age was postulated.

SAN ANTONIO SECTION SIXTH ANNUAL MEETING

The San Antonio Geological Society's sixth annual meeting and field trip were held on November 2–5 inclusive at Laredo, Texas. Two field trips, one through parts of south Texas, the day before the technical meeting at Laredo, and the other occupying two days, following the meeting, through northern Mexico and ending at Monterey, were well attended by members of the Society and numerous geologists from the Mid-Continent area.

The Texas field trip on Friday, November 2, started at Campbellton, 55 miles south of San Antonio, from which point sections of the Jackson (Eocene), Frio (Oligocene), and Catahoula and Oakville (Miocene) formations were studied. The Jacob, Calliham, Eagle Hill, and Government Wells fields were visited along this route. At noon, the Humble Oil and Refining Company furnished a barbecue at their North Government Wells camp to more than 100 geologists who made this trip.

The afternoon was spent in continuing the study of the Catahoula and Oakville (Miocene) formations southward, through the Saranosa, West Cole, and Cole fields, crossing the Bordas Escarpment and then turning west at Bruni and crossing the Claiborne (Eocene) section to reach Laredo that night. Very detailed road log and maps were furnished to those who made this trip.

On Saturday, November 3, more than 225 geologists were registered for the all-day technical session which was held in the Pan-American room of the Plaza Hotel at Laredo. The abstracts of papers dealing with the geology of south Texas and northern Mexico are printed on another page.

On Saturday afternoon, the 80 ladies who attended the meeting were entertained at a Mexican luncheon in the Hotel Rendon at Nuevo Laredo.

An informal dance was held on Saturday evening in the patio of the Hamilton Hotel with more than 200 in attendance. Entertainment was provided by native Mexican dancers.

On Sunday morning, 85 geologists in 30 automobiles started the two-day field trip through northern Mexico. Turning off the Laredo-Monterrey highway at Vallecillo, 64 miles south of Laredo, parts of the Upper Cretaceous and Eocene formations were studied and several well known structures, for example, Aldamas, La Presa, and Rancherias, were visited. The night was spent in bed-rolls at the Ohio-Mex camp at Rancherias, south of Rio Grande City, where supper and breakfast were furnished through the courtesy of the Ohio-Mexico Oil Company.

On the second day, Monday, November 5, the entire party crossed San Juan River by ferry at Camargo and continued the study of the Eocene and Oligocene section. An excellent barbecue was provided at the Sinclair-Mercedes camp at their Rio Bravo well No. 5 by Jack Burden of the Burden-Sheldon Drilling Company. The trip continued southwest along the Reynosa-Monterrey road, across the Oligocene, Eocene, and Upper Cretaceous section into Monterrey, which was reached late that night. Detailed road logs and maps were furnished those making this trip. Because of the rough roads, no ladies made the Mexico field trip but 30 ladies went direct from Laredo to Monterrey where a conducted tour was made of the mountain country including Horsetail Falls and Chipinque Mountain. The trip officially ended at Monterrey but several stayed over a few days and made short trips to Saltillo and near-by points.

The various committees who made possible the extremely interesting and instructive meeting and field trip of the San Antonio Section are to be congratulated.

The officers of the San Antonio Section are: president, T. J. Galbraith; vice-president, A. E. Getzendaner; secretary-treasurer, William H. Spice, Jr.; members of executive committee, Stuart Mossom and Julian Q. Myers.

The following committees made the arrangements for the sixth annual meeting.

General.—Olin G. Bell, chairman; Herschel H. Cooper, William G. Kane, Fred P. Shayes, Philip S. Schoeneck, and Worth W. McDonald.

Texas field trip.—Herschel H. Cooper, chairman; Stuart Mossom, and Kenneth H. Crandall.

Mexico field trip.—William G. Kane, chairman; G. B. Gierhart, S. Leonard, Ed. L. Porch, A. H. Petsch, H. M. Steig, and J. Laird Warner.

Program.—Fred P. Shayes, chairman; Chas. H. Row, A. E. Getzendaner.

Entertainment.—Philip S. Schoeneck, chairman; C. J. Cunningham and J. B. Whisenant.

Ladies entertainment.—Mrs. C. J. Cunningham, chairman; Mrs. Olin G. Bell, Mrs. Wm. G. Kane, Mrs. Philip Schoeneck, and Mrs. Wm. F. Calohan.

Transportation.—Worth W. McDonald, chairman; Geo. H. Sheldon and Mrs. Al Ferrando.

WILLIAM H. SPICE, JR.
Secretary-Treasurer, San Antonio Section

ABSTRACTS OF SAN ANTONIO SECTION PAPERS

The papers and abstracts are numbered as on the printed program of the San Antonio Section.

1. ED. W. OWEN, Discussion of Correlation Chart, Southwest Texas.
2. HENRY V. HOWE, The Relationship of the Vicksburg Group to the Formations which overlie it in Mississippi (abstract).

A certain amount of confusion in the nomenclature and in the correlation of certain formations encountered in deep wells in the Gulf Coastal areas which are now being exploited by oil development has necessarily occurred, perhaps primarily due to the fact that the more detailed stratigraphic and paleontological features of a number of the standard Tertiary sections of Mississippi and Alabama have not been known in greater comparative detail.

The exact demarcation of the upper and lower limits of the Oligocene is still a subject of controversy among paleontologists and geologists, particularly within the Gulf Coastal areas of Louisiana and Texas which are now undergoing exploitation by oil-field developments. It is particularly interesting that we may go to Mississippi for what appears to be the proper elucidation of the relationships of the standard Oligocene section of the Gulf Coastal Plains and the lowermost Miocene of Mississippi.

A marine formation lying between the Catahoula and the Byram marl of the Upper Vicksburg will be described. The evidence for the age of this formation and its position with respect to the *Heterostegina* zone will be discussed.

3. W. Armstrong Price, The Corpus Christi Structural Basin as Mapped by Salinity Data (abstract).

Water wells completed in the Lissie and Beaumont show artesian conditions to exist in spite of supposed lenticularity. Analyses of 1,400 water sands yield a salinity map based on regional, smoothed-out lines of equal chlorine concentration (iso-salinity lines) ranging up to 4,000 parts per million.

Inability to correlate individual sands requires that the Lissie-Beaumont be treated as a single water sand. Sands sampled lie beneath a shallow zone of highly saline ground-water which is invaded under sandy soil by fresh water. The strongest Lissie-Beaumont water analyzed has 6,200 parts and immediately beneath the Lissie is water with more than 22,000 parts of chlorine.

After analogy with the Woodbine artesian sand of the East Texas basin, where iso-salinity lines and structural contours are parallel, a wide swing of the lines around the head of Nueces-Corpus Christi Bay is taken to establish a Corpus Christi structural basin, provided the hypothesis of the down-dip flow of surface waters mixing with original oceanic brine is accepted as the explanation of the observed distribution of salinity in both regions.

Adjustment of the ancient, high-level delta of the Atascosa-Nueces rivers of the Pleistocene to the postulated structural basin, and entrenchment in it of the present Nueces River with its drowned-valley bays, support the structural interpretation of the salinity map. Outside the "basin" the lines are parallel with the gulf shore line. Barton's top-of-salt contours for salt domes indicate the other bays of Texas to be probably in structural basins.

Opposing interpretations are briefly discussed. The probably varied nature of the connate waters of the Pleistocene may require a combination of methods to explain the observed salinity gradients with their numerous local chlorine "highs." Two of the "highs" cover producing oil and gas fields. Others are believed to do so. Some are probably due to lenses of impervious sediments obstructing down-dip flow in the water sands. Their pattern does not seem to be that of shore-line features such as lagoon and bay basins, but superposition of many water sands which probably have varying salinities may have influenced the result. The structural interpretation of the local "highs" is not studied in detail.

4. J. B. WHISENANT, JOHN TRENCHARD, KENNETH H. CRANDALL, and E. C. RACH, Symposium on the Government Wells Field, Duval County (abstract).

This paper presents a short history of the field, its past development, drilling conditions, et cetera, and an explanation and discussion of cross sections through the north, central, and southern portions of the field.

Explanation of the subsurface structure includes areas underlain by various sand members. Also pertinent data on the completion of wells, initial pressure, potentials, operating conditions, various methods and their effect on recovery of the field, including loss of gas, are discussed.

Water encroachment and the ultimate recovery are discussed.

5. J. LAIRD WARNER, Geology of a Portion of the Tertiary of Northeastern Mexico (abstract).

Tentative contacts of some of the major groups and formations of the Tertiary age in northern Mexico. A brief discussion of the increase in thicknesses of practically every representative of each group and some suggestions as to the contact changes that may come about with further and more detailed study of the area.

6. FRITH C. OWENS and WM. F. CALOHAN, Claiborne Possibilities of the Laredo Area (abstract).

The discovery of commercial oil and gas production in the Claiborne section of southwest Texas and northern Mexico during the past year or two has brought this area into prominence. The various oil and gas producing horizons of this area are discussed and two cross sections prepared to show the relation of one field to another and correlate them with adjacent areas in northern Mexico.

The possibility of deep production on several relatively unknown structures in the area is pointed out together with notes on the older fields producing from the Claiborne section.

7 (No paper presented for this number).

8. RICHARD T. SHORT, The Cole Field, Webb County, Texas (abstract).

The area covered by this paper is located in southeastern Webb and southwestern Duval counties adjacent to the town of Bruni. The original discovery was made by the Cole Petroleum Company in their Benavides No. 4, in Survey 11, in July, 1924, which was completed as a gas well in a sand from 1,700 to 1,705 feet. In 1927 the Killam-Madox Bruni No. 1 in Survey 4 was completed as a gas well in a sand from 2,317 to 2,325 feet. Oil was subsequently discovered in the West Cole field in the same sand.

The discovery, in 1934, of gas by Allen and Morris at 2,950 feet in their Bruni No. 1 and oil in the United Production Company's Bruni No. 1 at 3,417 feet has started the development of the deeper sands.

The four sands now producing are the Cole sand (1,700-foot sand) at the top of the Jackson, the upper Mirando sand (2,300-foot sand at townsite of Bruni) in the lower part of the *Textularia hockleyensis* zone, the 2,950-foot sand in the Allen and Morris Bruni No. 1 which is near the top of the Yegua and the 3,400-foot sand in the United Production Corporation's Bruni No. 1 which is in the Yegua.

The major structural feature is an anticlinal fold the top of which is on the lines of Survey 5 and 8 about a mile southeast of the town of Bruni on which are located the recent oil wells completed in the 3,400-foot sand. The Cole sand (1,700) production is controlled by lensing and this is apparently the fact in the West Cole field where the upper Mirando sand is producing.

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Memorial

EDWIN MARTIN SHEPARD

Edwin Martin Shepard, for many years an outstanding figure in geological and educational circles in the Middle West, died at his home in Springfield, Missouri, April 28, 1934. He was born on May 15, 1854, in West Winstead, Connecticut.

Dr. Shepard attended Williams College, Williamstown, Massachusetts, where he received the degree of Bachelor of Arts, and in 1878 the degree of Master of Arts. He later majored in geology at Waynesburg College, Waynesburg, Pennsylvania, and there received the degree of Doctor of Science.

Some fifty years ago, Dr. Shepard became associated with Drury College at Springfield, Missouri, and in addition to his work in the department of geology he also served at various times in the capacity of librarian, dean, and, for a period of one year, acting president.

In addition to his academic work, Dr. Shepard attained distinction in the field of geology by his work for the United States Geological Survey and the Missouri Geological Survey, his publications for both organizations being of such clarity and soundness that several of them, although long since out of print, are used extensively as references in present-day geological work. He was vitally interested in the geology of Missouri, and his most outstanding contribution was his unfailing service to the State Geological Survey.

In 1901 he served as acting State geologist, and except for a short period he also served continuously as a member of the board of managers of the Missouri Geological Survey from 1893 until that board was abolished in 1933. He also served for many years as secretary of the board, and as chairman on the committee on publications. In the latter capacity he rendered particularly valuable service and, with his wide fund of knowledge and his characteristic clarity of expression, added much to the reports of the State Survey.

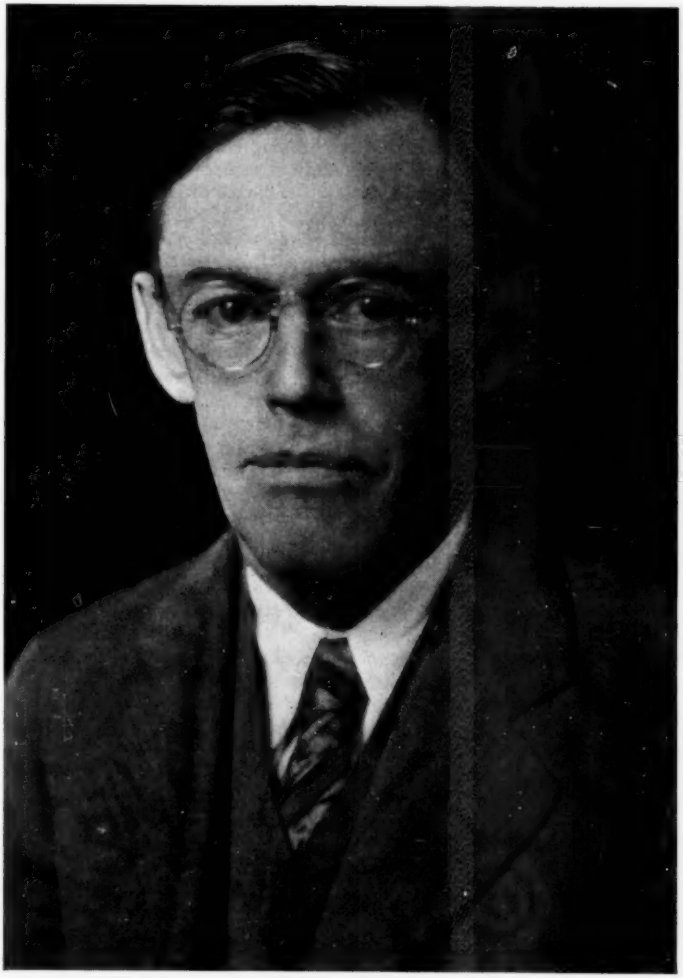
Even in his later years, Dr. Shepard was ever ready and eager to assist in every way toward the adequate maintenance of the State Survey, and with vigor and enthusiasm regularly attended every meeting of the board of managers, as well as all legislative sessions of interest to the organization.

Dr. Shepard was intensely interested, and particularly so in his later years, in the history and settlement of the Ozark region, and has published many articles which resulted from research in this field of investigation.

Shortly before his death, Dr. Shepard remarked to a close personal friend: "I'm through—my work is done." He leaves many outstanding monuments to his untiring efforts; a life full of achievement, and in the minds of his legion of friends the memory of an outstanding personality and a rare personal charm and dignity. He was ever the scholar, always the perfect gentleman, and withal a fine and loyal friend.

H. A. BUEHLER

ROLLA, MISSOURI
December 6, 1934



Charles Laurence Dake

CHARLES LAURENCE DAKE

Charles Laurence Dake, professor of geology at the Missouri School of Mines and Metallurgy, and a member of the American Association of Petroleum Geologists, died on September 3, 1934, in Denver, Colorado.

Professor Dake was born in Chaseburg, Wisconsin, April 2, 1883, the eldest son of George E. and Mary A. Dake. His father was a carpenter and builder, and in early life he started to learn this trade but soon afterward decided to enter the teaching profession. After completing his high school course, he spent 2 years at the State Normal School and then entered the University of Wisconsin, receiving his A.B. degree in 1911, and his A.M. the following year. In 1921, he was awarded the degree of Doctor of Philosophy by Columbia University. He was a member of Phi Beta Kappa, Sigma Xi, Phi Kappa Phi, Gamma Alpha, Acacia, The American Association of Petroleum Geologists, the American Institute of Mining and Metallurgical Engineers, and a Fellow of the Geological Society of America.

During his last year at Wisconsin he married Miss Ella Hildegarde Falkenstern, of Portage, Wisconsin.

In the fall of 1912 Dr. Dake received a temporary appointment as instructor in geology at Williams College. The following year he became assistant professor of geology at the Missouri School of Mines and Metallurgy. He was made associate professor in 1918, and professor and head of the department in 1921, a position which he held during the remainder of his life.

Dake was primarily an educator. His most important contribution to geology is to be found in the large number of professional geologists who began their training in his classrooms. He had a tremendous enthusiasm for his subject, and a clear and forceful manner of presentation. His students soon learned that it was not sufficient to be able to repeat what had been said in the lecture or what was contained in the text, for his examinations were almost invariably so framed as to require a student to reason from the facts rather than merely remember and repeat them. Small wonder that one of the students once remarked with a long face, "It's no use taking a 'crib' to Doc's exam, for you never can make one up to fit his questions."

Professor Dake's particular pride and hobby in teaching was his course in interpretation of topographic and geologic maps, and, in all probability, no better course in the subject has ever been given. It was an eye-opener for all who took it, and particularly to students who had entered with advanced standing and who had rashly tried (without success) to substitute work done elsewhere for it. Out of this course grew a very useful little text, *The Interpretation of Topographic and Geologic Maps*, written in collaboration with John S. Brown, a former student. Dake had long cherished the idea of writing a book which would be a revision and amplification of *United States Geological Survey Professional Paper 60*, and which would make use of the finer and more detailed topographic maps which had appeared since that volume had been published. The cost of such a volume was prohibitive, and no publisher would undertake it, and it was not until a plan was worked out whereby lists of available topographic maps were substituted for plates that it became possible. In their search for material for this book the authors examined practically every topographic and geologic map which had been published by the United States Geological Survey up to that time, as well as hundreds of maps from other sources.

Professor Dake took a keen interest in the educational standards of the department and of the school and was always on the alert to improve them. As head of the department, he was a member of the policy committee of the school, and he also served on the committees on graduate students and curricula. He was greatly interested in the whole problem of engineering education and at the time of his death was chairman of the American Institute of Mining and Metallurgical Engineers' committee on engineering education. Dake's own struggle for an education, against poverty and prejudice, has never been fully told, but it left its mark, and made him bitterly intolerant of the student who came to college "because he had to," or the one who "came to have a good time." He expected his students to show the same enthusiasm and industry that he himself possessed, and this was particularly true if the man had signified any intention of becoming a geologist. "I could give you a passing grade on this paper if you were merely taking the course because it is a required subject," he once told a student, "but, you have signified your intention of becoming a geologist, and I have a right to expect better work of you than of some of the others." He was always interested in the progress of his students, always willing and eager to discuss their problems with them, always ready to help them if possible, and managed, somehow or other, to keep in touch with many of them long after they had left school and entered professional work.

His own professional work was of high quality.

While a student at Wisconsin, he worked in the Iron Ranges both for the Wisconsin Geological Survey and for private companies. After coming to the Missouri School of Mines, most of his field seasons were spent in the employ of the Missouri Bureau of Geology and Mines. Out of this work came three large publications, "The Sand and Gravel Resources of Missouri," 1918; "The Problem of the St. Peter Sandstone," 1921; and "The Geology of the Potosi-Edgehill Quadrangles," 1930; material for a number of shorter papers, and a reputation as one of the outstanding students of the stratigraphy of the early Paleozoic of the Mississippi Valley. In the course of this work, he mapped the distribution of certain formations of the Ozark uplift in sufficient detail to permit their being shown separately on the 1922 edition of the "State Geologic Map," this being the first edition of this map in which such a separation had been attempted. Later studies in the Ozarks were partly responsible for the more detailed subdivision shown on the 1926 edition of this map.

The summer of 1916 was spent along the Rocky Mountain Front in northwestern Wyoming gathering data for a geological map of the state for the Wyoming Geological Survey. Out of this work came an important short paper, "The Heart Mountain Overthrust and Associated Structures in Park County, Wyoming," a clear description of one of the great overthrust faults of the northern Rockies, a type of structure whose existence in this region had not been clearly demonstrated before.

In 1917, in 1920, and again in 1930 he obtained a year's leave of absence from the school and spent the time in professional work, and in graduate study; the first year for the consulting firm of Valerius, McNutt, and Hughes; the second at Columbia University; the third in the employ of the Sinclair Company.

During the past summer he was again in northwestern Wyoming working on the Heart Mountain overthrust in collaboration with W. H. Bucher and

R. T. Chamberlin. This work was a part of the Yellowstone-Beartooth-Big Horn project, one of the several projects now being carried on with funds from the Penrose bequest to the Geological Society of America. He had been making a study of the distribution and nature of the "exotic" limestone masses along the mountain front between Greybull and Shoshone rivers, and mapping the critical thrust features in the valley of the South Fork of the Shoshone.

Dr. Dake was never a robust man, but his energy and enthusiasm for his work were tremendous. In the field he often drove himself to the point of exhaustion. He had completed his field work and was returning home with his wife, son, and two daughters when he was stricken with a cerebral hemorrhage, doubtless brought on by hard work in high altitudes, and died shortly after reaching the hospital in Denver.

In his death the Association has lost a loyal and devoted member, one who stood for all the ideals embodied in its code.

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JOSIAH BRIDGE

UNITED STATES GEOLOGICAL SURVEY
October 31, 1934

ALEX M. ALEXANDER

Alex M. Alexander, an active member of The American Association of Petroleum Geologists, met a sudden and untimely death in an explosion in a chemical laboratory in New York City on September 10, 1934. When this news reached his many friends in the Mid-Continent area, they were greatly shocked and grieved.

Alex was born June 2, 1898, in Baku, Russia. He attended the College of Agriculture in Petrograd, Russia, in 1916–17, majoring in natural science. His studies were interrupted by the revolution in Russia which brought suffering to himself and to his family. However, in 1918 he resumed his studies at the Polytechnic Institute at Odessa and remained there through 1920. His family being subjected to persecution, he escaped from Russia and came to the United States in 1920. For a certain period of time he very bravely sought work of any kind in New York while pursuing a study of English. After perfecting his knowledge of the language to a satisfactory degree, he attended the University of Pittsburgh, at Pittsburgh, Pennsylvania, and secured the degree of petroleum engineer in 1925.

From August, 1926, through December, 1928, he was employed by the Wentz Oil Corporation in Ponca City, Oklahoma, in their geological department. His work was varied, but he specialized particularly in magnetic investigation and research. From January, 1929, until March, 1932, he was employed in the geophysical department of the Empire Oil and Refining Company as geophysicist in charge of magnetic exploration and gravimetric and magnetic research. In all his work, Alex was very conscientious, careful, ingenious, and imbued with an insatiable desire to increase his knowledge. His ever-present sense of humor made him a very pleasant associate in work or recreation.

He became a naturalized American citizen in 1931 and was exceedingly

proud of this citizenship. To natural born Americans who take for granted this privilege, this pride was very refreshing and stimulating.

His life was beset with trials and difficulties which he strove successfully to overcome. It is very regrettable that he could not have lived to continue his progress in his chosen profession.

Alex is survived by his wife and a five-year-old daughter, who reside in Sunnyside, Long Island, New York.

G. H. WESTBY

TULSA, OKLAHOMA
November 9, 1934

BULLETIN OF THE AMERICAN ASSOCIATION OF PETROLEUM GEOLOGISTS
VOL. 19, NO. 1 (JANUARY, 1935), PP. 149-152

AT HOME AND ABROAD

PAUL E. FITZGERALD, who has been district manager for Dowell, Incorporated, at Shelby, Montana, is now in the research department of the company at Midland, Michigan.

GERALD N. SMITH is employed by the Western Geophysical Company, Los Angeles, California, and may be addressed at 1521 Northwest Thirty-First Street, Oklahoma City, Oklahoma.

N. E. BAKER has changed his address from 30 Rockefeller Plaza, New York City, to Iraq Petroleum Company, City Gate House, Finsbury Square, London, E. C. 2, England.

CLEO W. ECKENWILER, geologist with the Darby Petroleum Corporation, has been transferred from Houston, Texas, to Tulsa, Oklahoma.

PAUL T. SEASHORE, geologist for the Louisiana Land and Exploration Company, may now be addressed at Houma, Louisiana, where the company recently moved their offices from New Orleans.

ROY PAYNE recently left for Maracaibo, Venezuela, where he is employed by the Standard Oil Company of Venezuela.

JOSEPH M. DAWSON, zone agent for the Gulf Production Company, formerly at 1432 Milam Building, is now located at 1105 Alamo National Building, San Antonio, Texas, where the company recently moved the district offices.

W. D. CHAWNER has changed his address from 874 Adelaide Drive, Pasadena, California, to School of Geology, Louisiana State University, Baton Rouge.

HARRY B. FIELDS, formerly in the geological department of The Texas Company, Wichita, Kansas, may now be addressed at Ultramar S. A. P. A., 778 Calle Chile, Buenos Aires, Argentina, S. A.

FREDERICK W. PENNY has been retained as consulting geologist by Refoil Societate Anonima Romana, and may be addressed at Strada Eminescu No. 20, Ploesti, Roumania.

W. E. BAKKE, formerly of the North Penn Gas Company, Allegany, Pennsylvania, is now with the Oklahoma Oil Corporation, McCullough Building, Okmulgee, Oklahoma.

At a meeting of the Shreveport Geological Society, November 9, the following officers were elected for the year 1935: ROY T. HAZARD, president, Gulf Refining Company of Louisiana, Shreveport; G. D. THOMAS, vice-president, Shell Petroleum Corporation, Shreveport; PAUL NASH, secretary- treasurer, Magnolia Petroleum Company, Shreveport, Louisiana.

HARRY X. BAY, since leaving the service of Eastman, Gardner and Company, Laurel, Mississippi, on March 1, 1934, has been in the employ of the United States Geological Survey investigating the bleaching clays of Mississippi, Alabama, Georgia, South Carolina, and Florida.

DONALD C. BARTON, chairman of the research committee of the Association, led a round-table discussion on the migration or non-migration of oil and gas, at the regular monthly meeting of the San Antonio Geological Society, December 10, 1934.

At the regular meeting of the North Texas Geological Society at Wichita Falls, Texas, November 10, 1934, C. W. TOMLINSON, of Ardmore, Oklahoma, discussed "Bucher's Theories on Structure," and then applied them to conditions in southern Oklahoma. New officers were elected as follows: JOHN A. KAY, president, 828 Hamilton Building; J. F. GIBBS, Panhandle Oil Company, vice-president; CHARLES HOOKWAY, Magnolia Petroleum Company, secretary-treasurer.

VICTOR E. OPPENHEIM is consulting geologist for Serviço de Fomento da Producção Mineral, Avenida Pasteur 404, Rio de Janeiro, Brazil.

DEAN E. WINCHESTER, consulting geologist, 614 C. A. Johnson Building, Denver, Colorado, completed the season's work as engineeer in gold placer mining near Fair Play, Colorado. This work will be suspended until spring.

J. P. MCCULLOCH is chef du service des recherches de la Société des Raffinieres de Pétrole de la Gironde, 362 Rue St. Honoré, Cour Vendôme, Paris.

The American Society of Mechanical Engineers, 29 West 39th Street, New York, has published a timely and helpful pamphlet of 29 pages, *Finding Work*, by SAMUEL S. BOARD, dealing with a problem of paramount importance to the unemployed engineers in all fields. It may be procured from the publication sales department of the aforementioned society at 10 cents per copy. Another useful pamphlet that will be appreciated by parents and teachers, published by the Engineering Foundation's education research committee, is *Engineering: a Career, a Culture*, telling young men about engineering. The price is 15 cents.

At a meeting of the Oklahoma City Geological Society, December 3, 1934, the following officers were elected: president, JERRY B. NEWBY, 1816 West Twenty-Third Street; vice-president, RICHARD W. CAMP, Consolidated Gas Company; secretary-treasurer, A. J. MONTGOMERY, Phillips Petroleum Company.

T. S. LOVERING, of Golden, Colorado, is the author of United States Geological Survey Professional Paper 176, "Geology and Ore Deposits of the Breckenridge Mining District, Colorado," published last October.

JAMES H. GARDNER, of the Gardner Petroleum Company, Tulsa, and a past-president of the Association, gave a paper, "Origin and Development of Limestone Caverns," before the Tulsa Geological Society, December 3.

RUSSELL H. DICKEN is working for the Plymouth Oil Company in San Antonio, Texas.

GERALD H. WESTBY, vice-president of the Seismograph Service Corporation, Tulsa, Oklahoma, gave a radio talk on geophysics at the Tulsa Chamber of Commerce luncheon, December 7.

At the eleventh annual meeting of the Pacific Section of The American Association of Petroleum Geologists, the following officers were elected for the year 1935: HAROLD W. HOOTS, president, Union Oil Company of California, Los Angeles; GRAHAM B. MOODY, secretary-treasurer, Standard Oil Company of California, Los Angeles, California.

BASIL B. ZAVOICO, consulting geologist, presented a paper on "Geology and Development of the Lucien Field," before the Tulsa Geological Society, December 17, 1934.

New officers of the West Texas Geological Society are the following: president, CHARLES D. VERTREES, Continental Oil Company, Midland; vice-president, F. H. MCGUIGAN, Shell Petroleum Corporation, San Angelo; and GEORGES VORBE, Stanolind Oil and Gas Company, Midland.

NORMAN L. THOMAS presented his paper, "Correlations in East Texas Basin," before the Fort Worth Geological Society, December 17, 1934.

B. F. HAKE is in the employ of the Eastern Gulf Oil Company at Saginaw, Michigan.

At the annual meeting of the Texas Academy of Science in Austin on November 17, the following members of the Association or its Division of Paleontology and Mineralogy were elected to office in the Academy: executive vice-president, W. M. WINTON, of Texas Christian University, Fort Worth; vice-president of the section of Geological Sciences, W. ARMSTRONG PRICE, consulting geologist, Corpus Christi; secretary, FREDERICK A. BURT, of the Agricultural and Mechanical College, College Station; editor, Mrs. HELEN JEANNE PLUMMER, University of Texas, Austin. J. C. GODBEY, Southwestern University, Georgetown, is president of the Academy.

Last fall, the bureaus of Economic Geology, Industrial Chemistry, and Engineering Research, constituting the Division of Natural Resources of The University of Texas, completed a quarter century of service in the study of the mineral resources of Texas. To commemorate this event, the three bureaus, with the aid of the associated departments of Geology, Chemistry, and the College of Engineering presented a program of scientific papers devoted to the industrial development of Texas.

The Tulsa Geological Society has elected the following officers for 1935: president, EDWARD BLOESCH, consulting geologist, Kennedy Building; first vice-president, JOSEPH L. BORDEN, Pure Oil Company; second vice-president, GLENN S. DILLE, Texas Company; secretary-treasurer, SAM H. WOODS, Twin State Oil Company; editor, THOMAS C. HIESTAND, W. C. McBride, Inc.; councilors, W. E. HORKEY, Fisher Oil Company, and GERALD H. WESTBY, Seismograph Service Corporation.

JOHN H. WILSON, of the Colorado Geophysical Corporation, Denver, associated with the Independent Exploration Company, Houston, Texas, read a paper on "Geology and Oil Possibilities of Eastern Colorado," before the West Texas Geological Society at Midland, January 3.

PHILIP B. KING, of the United States Geological Survey, read a paper on the "Quadalupe Mountain Region," before the New Mexico Geological Society at Carlsbad, January 12.